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January 1950

THE SYSTEM $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ [1]

VEI CHOW JUAN
University of Peking

ABSTRACT

The thermal-equilibrium relationships in the system $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ have been investigated by the quenching method. The data are tabulated, and the results are presented in equilibrium diagrams. Complex solid solutions in the crystalline phases, with the exception of pseudowollastonite, render the system nonternary, and the courses of crystallization must be viewed in terms of the quaternary system of the four component oxides. The bearing of the results of the present study on related systems of the soda-lime-alumina-silica tetrahedron and the petrologic significance are discussed.

INTRODUCTION

This investigation is concerned with the thermal-equilibrium relationships, at atmospheric pressure, of the three silicates, $CaSiO_3$, $Ca_2Al_2SiO_7$, and $NaAlSiO_4$. These compounds are the fundamental molecules of the natural minerals wollastonite, gehlenite, and nepheline, respectively. Nepheline and the melilites, of which gehlenite is an end-member, are feldspathoids that are associated in certain alkaline rocks, whereas wollastonite is typically a contact metamorphic mineral. Nevertheless, wollastonite has been described as a primary constituent of certain alkaline rocks and is associated with nepheline in such occurrences.

The compounds involved in this study that exhibit polymorphism are $CaSiO_3$ and $NaAlSiO_4$. Carnegieite, the high-temperature modification of $NaAlSiO_4$, occurs only in synthetic melts. Pseudowollastonite, the high-temperature modification of $CaSiO_3$, has been reported in one unique occurrence in nature (McLintock, 1932).

The system constitutes a portion of a plane within the quarternary system, soda-lime-alumina-silica, which may be represented by a composition tetrahedron as shown in figure 1. This figure also shows the position of the system studied in the tetrahedron and its relationship to other investigated systems. The system wollastonite-gehlenite-nepheline forms one face of a subsidiary tetrahedron, anorthite-gehlenite-wollastonite-nepheline, within the quaternary system, and the plane anorthite-nepheline-wollastonite is common to a second subsidiary tetrahedron, anorthite-nepheline-wollastonite-albite. The system $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ lies in the same plane as the system $CaSiO_3$-$NaAlSiO_4$-"$Na_2Si_2O_7$," and the two are adjacent, because the "binary" system wollaston-

[1] Manuscript received February 24, 1949. The work on which this paper is based was done at the University of Chicago in 1945 and 1946, before more recent papers bearing on the subject were published.

ite-nepheline is common to both. Investigation of this "binary" system indicated that relationships departed somewhat from binary behavior as a result of interaction between wollastonite and nepheline (Foster, 1942). The reaction was confirmed by the investigations of the system wollastonite-nepheline-sodium metasilicate (Spivak, 1944) and the system wollastonite-anorthite-nepheline (Gummer, 1943). Another complication results from the complex solid solutions in nepheline and gehlenite, a phenomenon encountered previously in the investigation of the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ (Smalley, 1947) and the system $CaAl_2Si_2O_8$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ (Goldsmith, 1947).

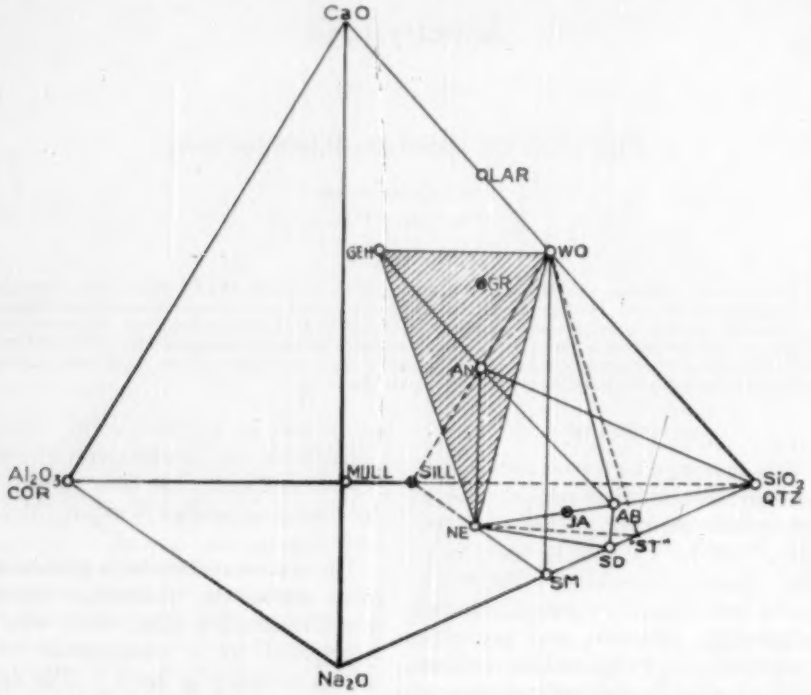

FIG. 1.—The soda-lime-alumina-silica tetrahedron. The shaded area indicates the position of the system gehlenite-nepheline-wollastonite within the tetrahedron. Other internal systems that have been investigated are shown by solid lines joining the composition points. The compounds that have been prepared synthetically are shown as ○; those that occur in nature but do not form at liquidus temperatures are shown as ⊕. Abbreviations: *LAR*, larnite; *Wo*, wollastonite; *Geh*, gehlenite; *GR*, grossularite; *An*, anorthite; *Sill*, sillimanite; *Mull*, mullite; *NE*, nepheline; *SM*, sodium metasilicate; *JA*, jadeite; *QTZ*, quartz; *Cor*, corundum; *AB*, albite; *SD*, sodium disilicate; "*ST*," "sodium trisilicate," though this does not exist as a compound.

THE THERMAL DATA

The systems $NaAlSiO_4$-$CaSiO_3$ and $NaAlSiO_4$-$Ca_2Al_2SiO_7$ were investigated by Foster (1942) and by Smalley (1947), respectively, and the binary system $Ca_2Al_2SiO_7$-$CaSiO_3$ was investigated by E. F. Osborn and J. F. Schairer (1941, p. 719) in their work on the system

pseudowollastonte-akermanite-gehlenite. These authors' data are here used in constructing the equilibrium diagrams (figs. 2, 3, and 4). The properties of the crystalline phases are tabulated in table 1.

In the thermal investigation of the equilibrium relationships in the system $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$, thirty-six platinum-platinum 90 rhodium 10 thermoelement, calibrated against the melting points of lithium metasilicate (1,201° C.) and diopside (1,391°.5 C.).

Of the 154 runs which were made, about half were sufficient to determine the temperatures of the various transformations. The results of these critical runs

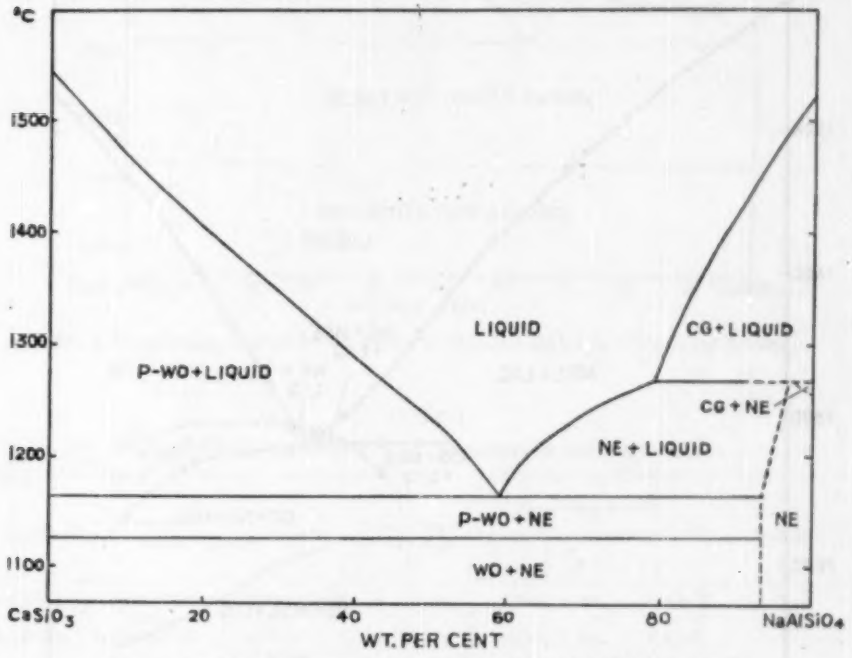

FIG. 2.—Equilibrium diagram for the system $CaSiO_3$-$NaAlSiO_4$ (after Foster)

mixtures of different composition were prepared and studied. The values of the refractive indices of the glasses prepared for the runs have been determined and plotted on a composition–refractive-index diagram (fig. 5). The mixtures were subjected to thermal study by means of the quenching method as developed in the Geophysical Laboratory of the Carnegie Institution of Washington (Shepherd, Rankin, and Wright, 1909, p. 308). Temperatures were measured with a

are presented in table 2. The equilibrium diagrams based on these results appear as figures 6 and 7. In figure 6 the isotherms are drawn at 50° intervals, whereas in figure 7 the isotherms have been omitted, and the stability fields and arrows indicating the directions of falling temperatures are shown.

NONTERNARY NATURE OF THE SYSTEM

Carnegieite and nepheline form solid solutions that cannot be expressed in

terms of the three end-members. A field of melilite is present rather than one of pure gehlenite. There is, therefore, a great deal of complication in this system; the composition of any liquid during crystallization does not remain in the plane defined by the three end-members, and the exact course of crystallization for many mixtures can be described only in terms of the parent-system, soda-lime-alumina-silica.

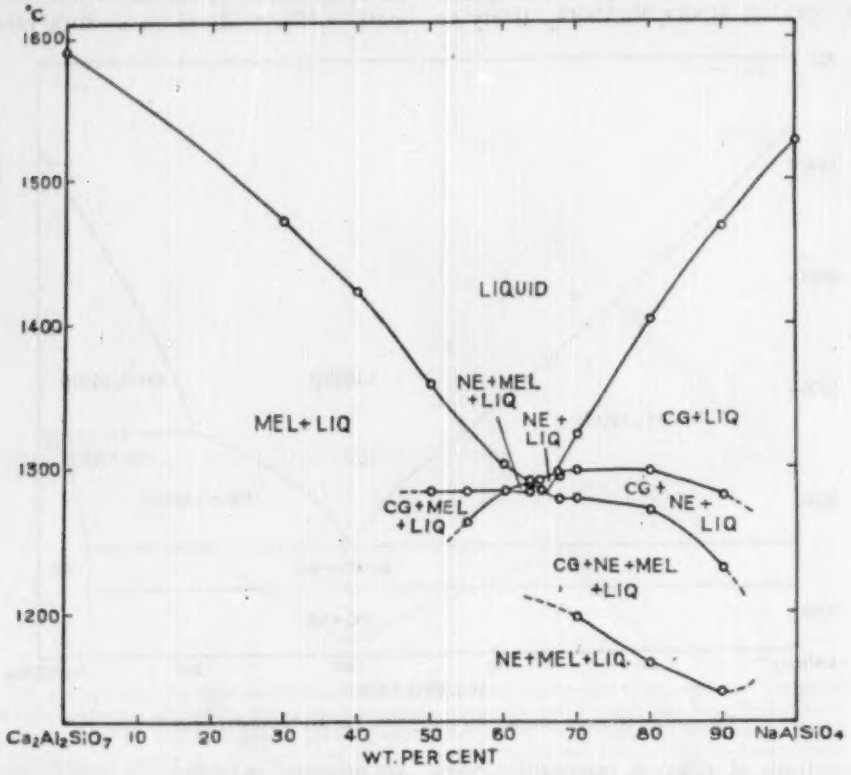

FIG. 3.—Equilibrium diagram for the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ (after Smalley)

THE LIQUIDUS RELATIONS

Four fields of the primary phases have been outlined in order of decreasing size —melilite, pseudowollastonite, carnegieite solid solutions, and nepheline solid solutions. Wollastonite was not encountered, a fact which indicates that no substance enters into solid solution in the wollastonite to raise the inversion temperature appreciably. In figure 6 the configuration of the fusion surfaces of the fields can be ascertained from the isotherms.

A maximum is present on the boundary curve between the fields of pseudowollastonite and nepheline solid solutions, at about 6 per cent gehlenite at a temperature of 1,182 ± 2° C. It is about

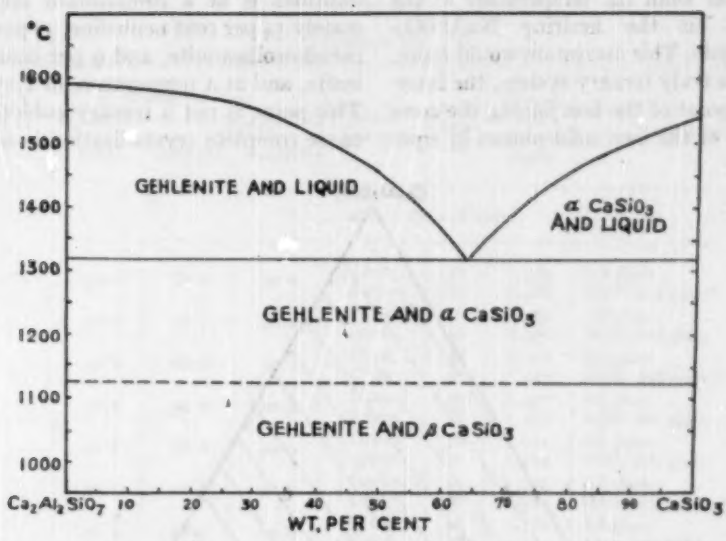

FIG. 4.—Equilibrium diagram for the system $CaSiO_3$-$Ca_2Al_2SiO_7$ (after Osborn and Schairer)

TABLE 1

CRYSTALLOGRAPHIC AND OPTICAL PROPERTIES OF THE SOLID PHASES

COMPOUND	CRYSTAL SYSTEM	HABIT	ELONGATION	OPTIC SIGN	REFRACTIVE INDICES			REMARKS
					α	β	γ	
α-$CaSiO_3$	Pseudohexagonal	Plates or laths	−	+	1.610	1.611	1.634*	
β-$CaSiO_3$	Monoclinic	Laths or needles	+	−	1.616	1.629	1.631†	
α-$NaAlSiO_4$	Isometric (above 690°)	Globules	.....	−	1.509	.....	1.514‡	Grating twinning characteristic
β-$NaAlSiO_4$	Hexagonal	Hexagonal plates or rectangular prisms	.....	−	ε = 1.533	.....	ω = 1.537§	
$Ca_2Al_2SiO_7$	Tetragonal	Prisms or plates	+ and −	−	ε = 1.658	.....	ω = 1.669‖	Globules and ditetragonal plates are typical

* Ferguson and Merwin (1919), p. 83.
† Allen, White, and Wright (1906), p. 108.
‡ Bowen (1912), pp. 551–573.
§ *Ibid.*, p. 563.
‖ Osborn and Schairer (1941), p. 710.

18° higher than the temperature of the eutectic on the limiting $NaAlSiO_4$-$CaSiO_3$ join. This maximum would represent, in a truly ternary system, the intersecting point of the line joining the composition of the two solid phases in equilibrium with the liquid on the boundary curve having the composition of this point of maximum temperature. In the present case this relation does not hold because the composition of the nepheline solid solution does not lie in the plane of the system.

The junction of the fields of melilite, pseudowollastonite, and nepheline solid solutions is at a composition approximately 54 per cent nepheline, 37 per cent pseudowollastonite, and 9 per cent gehlenite, and at a temperature of 1,174° C. This point is not a ternary eutectic because complete crystallization is not attained at that temperature and the point does not represent the composition of the last liquid. It is but the point where the plane of the system is pierced by the univariant boundary curve between the quarternary fields of nepheline solid solutions, melilite, and pseudowollastonite.

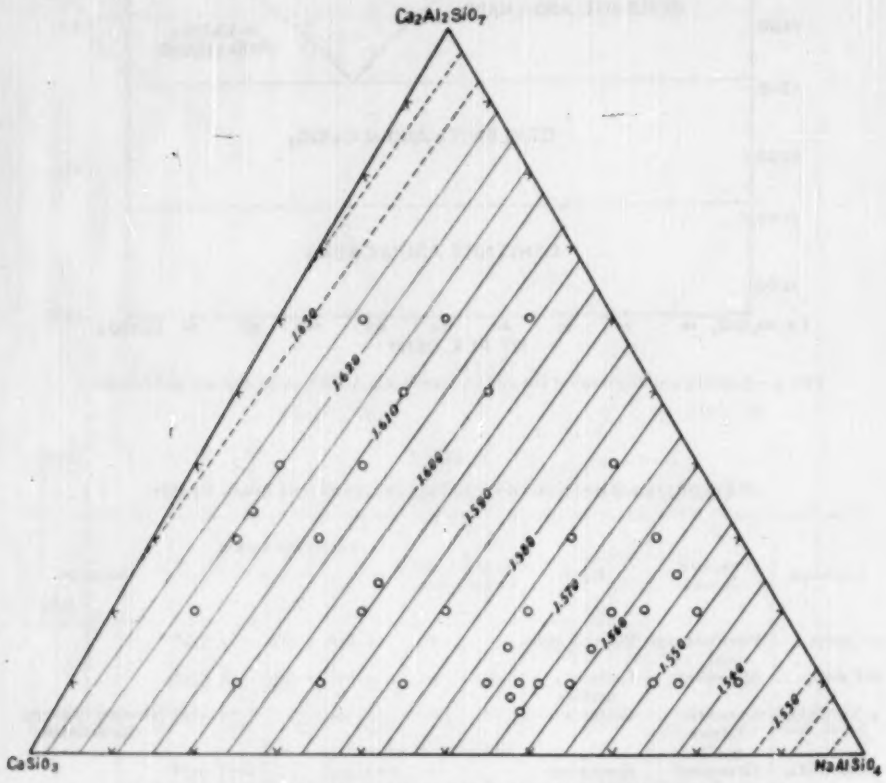

FIG. 5.—The composition-refractive index diagram for the glass mixtures

From the evidence obtained in the study of the system $CaSiO_3$-$CaAl_2Si_2O_8$-

TABLE 2

THERMAL DATA

Refractive Index of Glass	Weight Per Cent			Initial Condition	Time (Minutes)	Temperature (Centigrade)	Final Condition
	$CaSiO_3$	$Ca_2Al_2SiO_7$	$NaAlSiO_4$				
	Primary-Phase Melilite						
1.612	30.0	60.0	10.0	Glass	50	1,487	All glass
				Glass	30	1,482	MEL and glass
1.612	20.0	60.0	20.0	Glass	30	1,467	All glass
				Glass	40	1,462	MEL and glass
1.602	10.0	60.0	30.0	Glass	30	1,446	All glass
				Glass	30	1,440	MEL and glass
1.612	30.0	50.0	20.0	Glass	30	1,437	All glass
				Devitr.	30	1,432	MEL and glass
1.598	20.0	50.0	30.0	Devitr.	30	1,414	All glass
				Devitr.	30	1,409	MEL and glass
1.608	40.0	40.0	20.0	Devitr.	30	1,373	All glass
				Glass	30	1,369	Rare MEL and glass
1.618	50.0	40.0	10.0	Glass	30	1,367	All glass
				Glass	30	1,362	Very rare MEL and glass
1.574	10.0	40.0	50.0	Glass	45	1,340	All glass
				Glass	30	1,334	Rare MEL and glass
1.574	20.0	30.0	50.0	Devitr.	30	1,308	All glass
				Devitr.	30	1,302	MEL and glass
1.619	56.0	34.0	10.0	Glass	30	1,303	All glass
				Glass	40	1,297	Rare MEL and glass
1.607	50.0	30.0	20.0	Glass	35	1,295	All glass
				Glass	35	1,290	Rare MEL and glass
1.562	10.0	30.0	60.0	Devitr.	30	1,286	All glass
				Devitr.	30	1,282	MEL and glass
				Devitr.	25	1,276	MEL and glass
				Devitr.	30	1,251	MEL, NE, and glass
1.595	46.0	24.0	30.0	Devitr.	30	1,264	All glass
				Devitr.	30	1,259	Rare MEL and glass
1.573	30.0	20.0	50.0	Devitr.	35	1,256	All glass
				Glass	40	1,250	Rare MEL and glass
1.560	20.0	20.0	60.0	Devitr.	30	1,245	All glass
				Devitr.	30	1,238	Rare MEL and glass
1.583	40.0	20.0	40.0	Devitr.	30	1,243	All glass
				Devitr.	30	1,238	MEL, P-Wo, and glass
1.562	25.0	15.0	60.0	Devitr.	35	1,228	All glass
				Devitr.	30	1,223	MEL, NE, and glass
1.565	34.0	10.0	56.0	Devitr.	25	1,200	All glass
				Devitr.	30	1,196	MEL, NE, and glass
1.572	35.0	15.0	50.0	Devitr.	30	1,205	All glass
				Devitr.	30	1,199	Rare MEL and glass
1.567	36.0	10.0	54.0	Devitr.	30	1,192	Rare MEL and glass
				Devitr.	30	1,178	Rare MEL, NE, and glass
				Devitr.	35	1,174	MEL, NE, P-Wo, and glass

TABLE 2—*Continued*

Refractive Index of Glass	Weight Per Cent			Initial Condition	Time (Minutes)	Temperature (Centigrade)	Final Condition
	$CaSiO_3$	$Ca_2Al_2SiO_7$	$NaAlSiO_4$				
	Primary-Phase Pseudowollastonite						
1.616	70.0	20.0	10.0	Glass	30	1,365	All glass
				Glass	35	1,359	Rare P-Wo and glass
1.605	70.0	10.0	20.0	Devitr.	40	1,354	All glass
				Devitr.	30	1,350	Rare P-Wo and glass
1.617	60.0	30.0	10.0	Glass	30	1,295	All glass
				Glass	30	1,292	Very rare P-Wo and glass
1.593	60.0	10.0	30.0	Devitr.	40	1,287	All glass
				Devitr.	30	1,283	P-Wo and glass
1.583	50.0	10.0	40.0	Devitr.	30	1,233	All glass
				Devitr.	30	1,229	P-Wo and glass
1.593	50.0	20.0	30.0	Glass	45	1,231	All glass
				Devitr.	30	1,229	Rare P-Wo and glass
1.572	40.0	10.0	50.0	Devitr.	35	1,190	All glass
				Glass	30	1,187	P-Wo, MEL, and glass
1.568	38.0	8.0	54.0	Devitr.	30	1,186	All glass
				Devitr.	30	1,180	Rare P-Wo and glass
				Devitr.	30	1,178	Rare P-Wo and glass
				Glass	30	1,163	P-Wo, NE, and glass
	Primary-Phase Carnegieite						
1.539	10.0	10.0	80.0	Glass	30	1,350	All glass
				Glass	30	1,346	Rare CG and glass
1.551	10.0	20.0	70.0	Glass	30	1,295	All glass
				Devitr.	40	1,294	Rare CG and glass
				Glass	30	1,262	CG, NE, and glass
1.547	17.0	10.0	73.0	Devitr.	35	1,282	All glass
				Devitr.	40	1,279	Rare CG and glass
				Devitr.	40	1,261	CG, NE, and glass
	Primary-Phase Nepheline						
1.537	10.0	25.0	65.0	Devitr.	35	1,270	All glass
				Devitr.	30	1,265	NE and glass
1.548	20.0	10.0	70.0	Devitr.	30	1,260	All glass
				Devitr.	35	1,256	NE and glass
1.558	16.0	20.0	64.0	Devitr.	30	1,269	All glass
				Devitr.	30	1,264	NE and glass
				Devitr.	30	1,259	NE and glass
				Devitr.	30	1,239	NE, MEL, and glass
1.562	25.0	15.0	60.0	Devitr.	35	1,228	All glass
				Devitr.	30	1,223	NE, MEL, and glass
1.560	30.0	10.0	60.0	Devitr.	30	1,214	All glass
				Devitr.	35	1,210	Rare NE and glass
1.565	34.0	10.0	56.0	Devitr.	25	1,200	All glass
				Devitr.	30	1,196	NE, MEL, and glass
1.564	38.0	6.0	56.0	Devitr.	30	1,184	All glass
				Devitr.	35	1,179	NE and glass
				Devitr.	30	1,173	NE and glass
				Devitr.	30	1,167	NE, P-Wo, and glass

$NaAlSiO_4$ investigated by Gummer (1943), the field of gehlenite plunges across the face $CaSiO_3$-$CaAl_2Si_2O_8$-$NaAlSiO_4$ of the subsidiary tetrahedron, anorthite - gehlenite - nepheline - wollastonite, and the boundary curve between melilite, pseudowollastonite, and nepheline solid solutions pierces that plane at a temperature of 1,169° C. For approximate purposes, the line joining the point at 1,174° and that at 1,169° C. thus locates part of the pseudowollastonite-melilite-nepheline boundary curve in the general tetrahedron.

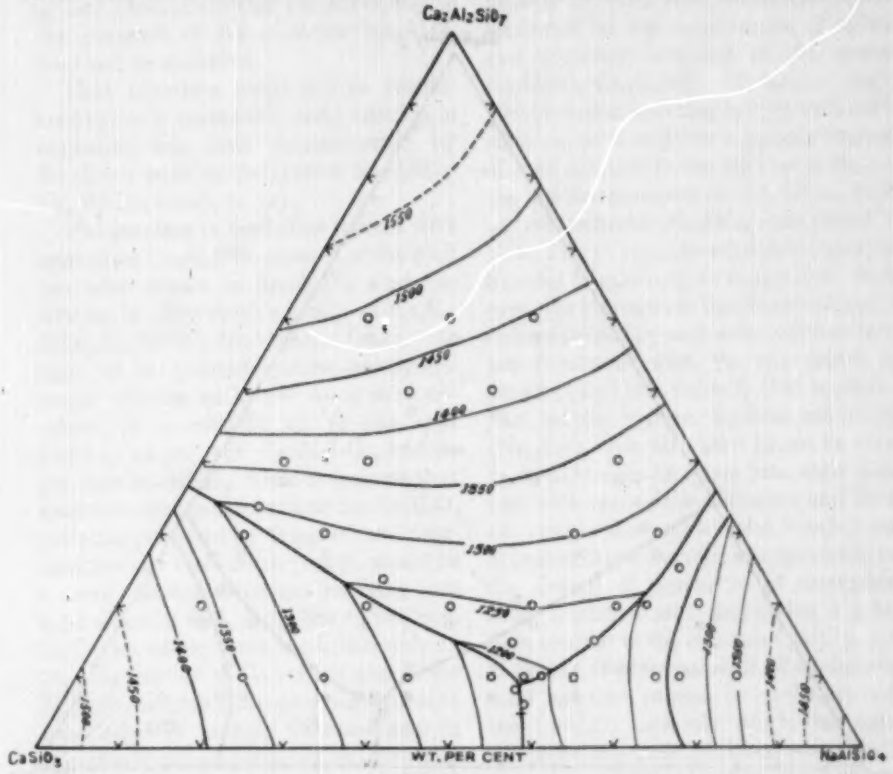

FIG. 6.—Equilibrium diagram for the system $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$, with isotherms

COURSES OF CRYSTALLIZATION

It is not possible to give a precise description of the course of crystallization viewed in three dimensions within the quaternary system because we do not know the exact composition of those crystalline phases which lie outside the plane of the system. No attempt has been made to locate in space the pseudowollastonite-melilite-nepheline boundary curve in order to obtain the data on the courses of crystallization, as was done by Goldsmith (1947).

THE SUBSTANCES IN SOLID SOLUTION

Frequent demonstration has been made of the fact that pure end-members are never formed in synthetic melts when there are substances present with which they may form solid solutions. In the foregoing it has been mentioned that the crystalline phases of this system are solid solutions, with the possible exception of pseudowollastonite. The nature of substances in solid solution in nepheline and carnegieite of this system is unfortunately not settled by the results of this study, but certain data do suggest a limit to the possibilities. A choice among the unknown molecules in solid solution with gehlenite may also be made.

NEPHELINE

Of the molecules entering into the composition of natural nephelines, $KAlSiO_4$ is known to form a complete series of solid solutions with $NaAlSiO_4$ (Bowen, 1917), and experimental work has also shown that 35 per cent each of albite (Greig and Barth, 1938, p. 106) and anorthite (Bowen, 1912, p. 563) are taken into solid solution. In the present system, potash compounds are excluded as a possibility. Plagioclase may be sufficient to account for the excess silica, as

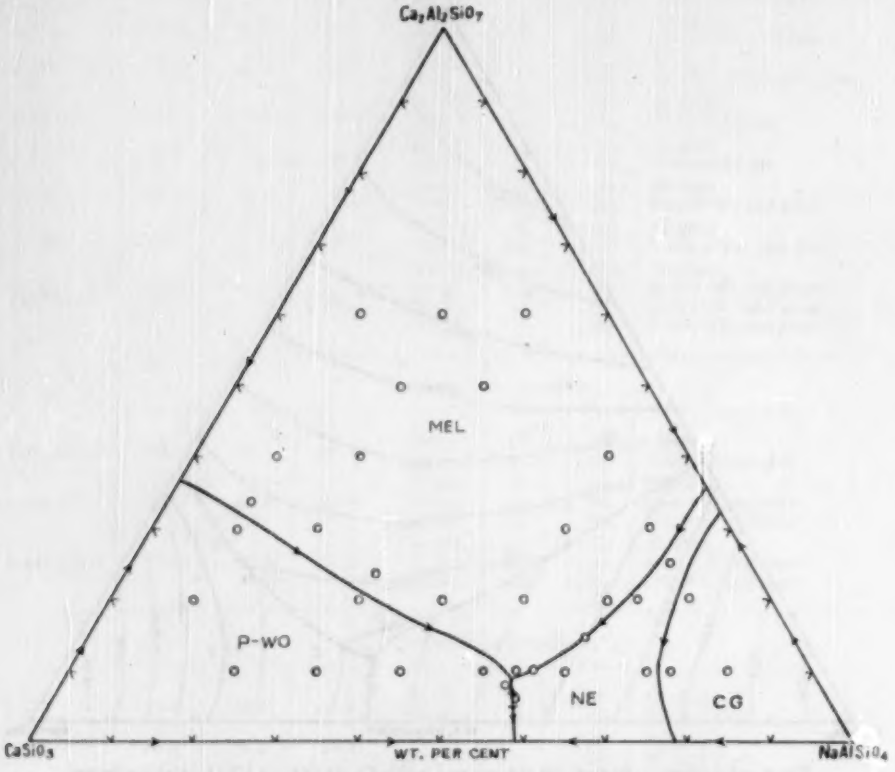

FIG. 7.—Equilibrium diagram for the system $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$, with isotherms omitted

well as the calcium that is found in natural nepheline, as it is known to change the refractive indices of nepheline when in solid solution with it, but A. N. Winchell (1933, p. 297) has suggested that the molecule $CaAl_2O_4$ may play a part in the composition, and Goldsmith (1947, p. 400) pointed out that the possibility of the presence of the molecule $Na_2Al_2O_4$ may not be excluded.

That anorthite could not be considered the only material in solid solution in nepheline has been demonstrated by Smalley's work on the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ (1947, p. 34).

The increase in nepheline indices with increasing $Ca_2Al_2SiO_7$ content of the melt has been shown in Smalley's work, as well as in Goldsmith's study of $CaAl_2Si_2O_8$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ (1947, p. 399). In the present system, nearly isotropic crystals with $n = 1.559$ were obtained in a mixture at 30 per cent $CaSiO_3$, 10 per cent $Ca_2Al_2SiO_7$, and 60 per cent $NaAlSiO_4$. Thus it appears that a calcium aluminate, such as the $CaAl_2O_4$ molecule proposed by Winchell and demonstrated by Goldsmith (1949), would be a more suitable substance entering into solid solution with nepheline in this system. This differs from nepheline only in the substitution of Ca for Na and Al for Si, replacements consistent with present knowledge of atomic volumes and in agreement with the effect on indices upon addition of calcium compounds. This compound may be thought of as produced by interaction between wollastonite, nepheline, and gehlenite as expressed by the equation

$$CaSiO_3 + Ca_2Al_2SiO_7 + 4NaAlSiO_4 \rightarrow 2CaAl_2Si_2O_8 + 2Na_2SiO_3 + CaAl_2O_4.$$

It is known that Na_2SiO_3, although it enters into carnegieite solid solution, does not form solid solution with nepheline (Tilley, 1933, p. 414). Therefore, Na_2SiO_3 must remain in the residual liquid as a result of the above reaction.

CARNEGIEITE

Carnegieite solid solutions pose a problem very similar to that of nepheline mix-crystals. The modification of carnegieite by solid solution has been demonstrated by the marked rise of indices and inversion lowering in the system $NaAlSiO_4$-$Ca_2Al_2SiO_7$ (Smalley, 1947). The inversion lowering is very unusual in silicates, as it requires a greater amount of solid solution in the high form than in the low-temperature modification. Sodium metasilicate (Na_2SiO_3) was found by C. E. Tilley (1933) to enter into carnegieite solid solutions up to 24 per cent. However, the increases in birefringence and in indices caused by such solid solution were not consistent with the rise found by Smalley, and it is unlikely that it plays a part in this system. Sodium aluminate ($Na_2Al_2O_4$) has also been found to enter in considerable amounts into solid solution with carnegieite (Schairer and Bowen, unpublished work); and Smalley has accepted this substance as responsible for the change of properties of carnegieite solid solutions with increasing $Ca_2Al_2SiO_7$ content of the mixture (1947, p. 35). However, the formation of a lime-bearing solid solution cannot be excluded, and the $CaAl_2O_4$ molecule which can enter into nepheline solid solutions may also be present in the carnegieite mix-crystals.

GEHLENITE

A progressive decrease in index of melilite with increasing soda content has been observed by Goldsmith (1947, pp. 400–401) in the system $Ca_2Al_2Si_2O_8$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$ and by Smalley in the limiting $Ca_2Al_2SiO_7$-$NaAlSiO_4$ system. The melilites that crystallize in the present system, as shown in table 3, also follow this trend. The melilite formed

from a mixture of composition 30 per cent pseudowollastonite, 60 per cent gehlenite, and 10 per cent nepheline had indices $\omega = 1.668$, $\epsilon' = 1.656$; and in the composition 30 per cent pseudowollastonite, 50 per cent gehlenite, and 20 per cent nepheline the indices were $\omega = 1.658$, $\epsilon' = 1.656$; at 36 per cent pseudowollastonite, 10 per cent gehlenite, and 54 per cent nepheline, $\omega = 1.650$, $\epsilon' = 1.648$.

In nature, gehlenite shows a strong tendency to form complex solid solutions, and several theories have been advanced in regard to the hypothetical molecules in melilites. A complete series of solid solutions exists between $Ca_2Al_2SiO_7$ (gehlenite) and $Ca_2MgSi_2O_7$ (akermanite), but for the present discussion the magnesia-bearing compounds, as well as the iron melilites, will be excluded. The sarcolite molecules, which had been proposed earlier by W. T. Schaller (1916) and supported later by A. F. Buddington (1922), were discredited by A. N. Winchell (1924) on the ground of dissimilarity in atomic volumes. In applying the idea of volume isomorphism, Winchell proposed the molecules $Ca_3Si_2O_7$, $Na_2Si_2O_7$, and $NaCaAlSi_2O_7$, all conforming to the general formula R_4O_7 of the melilites. Berman in 1929 viewed the problem and modified Winchell's fundamental R_4O_7 to $X_2Y_3O_7$ for all melilites. He accepted the molecule $Na_2Si_3O_7$ but offered $CaSi_3O_7$ in place of $Ca_3Si_2O_7$ to explain the excess silica and deficiency of calcium and sodium found in natural melilites. On the basis of chemical analyses, Berman stated that the soda melilite ($Na_2Si_3O_7$) is present up to 25 per cent in natural occurrences, and submelilite ($CaSi_3O_7$) not over 10 per cent. In general, Berman's molecules fit rather well with the available analyses of natural melilites. Goldsmith (1947, pp. 401–403) indicated, in connection with the study of the system $CaAl_2Si_2O_8$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$, the molecule $CaAl_4O_7$ as the substance in solid solution in gehlenite, though it was admitted that no solid solutions of this nature were encountered in the investigation of the system CaO-Al_2O_3-SiO_2 (Rankin and Wright, 1915), and the substitution of Al for Ca in the solid solution is not in conformity with the idea of volume isomorphism.

Although no attempt has been made to determine "four-phase boundaries" for the purpose of obtaining information on the nature of the melilite mix-crystals in this system, the general location of the

TABLE 3

GEHLENITE SOLID SOLUTIONS

Weight Per Cent*			Indices		Elongation	Optical Sign	Birefringence	Crystal Form
$CaSiO_3$	$Ca_2Al_2SiO_7$	$NaAlSiO_4$	ω	ϵ'				
30.0	60.0	10.0	1.667	1.656	+	−	0.011	Prismatic, tabular
30.0	50.0	20.0	1.658	1.656	+	−	0.002	Tabular, prismatic, globular
10.0	40.0	50.0	1.652	1.650	+	−	0.002	Tabular, prismatic
20.0	30.0	50.0	1.657	1.653	+	−	0.004	Tabular, prismatic
20.0	20.0	60.0	1.658	1.656	+	−	0.002	Tabular, prismatic
35.0	15.0	50.0	1.653	1.652	+	−	0.001	Tabular, prismatic
36.0	10.0	54.0	1.650	1.648	+	−	0.002	Tabular, prismatic

* Being total composition of the mixture from which gehlenite crystallized; the actual composition of the gehlenite itself is, in each case, not determined.

quaternary boundary curve between melilite, pseudowollastonite, and nepheline solid solutions may serve to indicate in what ways the compositions of the liquids may change as the mix-crystals separate out.

Consideration of crystallization of liquids in the melilite field lends support to the probability of the formation of the $Na_2Si_3O_7$ molecule. The supposed formation of $Na_2Si_3O_7$ solid solution in gehlenite by partial reaction according to the equation

$$CaSiO_3 + Ca_2Al_2SiO_7 + 4NaAlSiO_4 \rightarrow 3CaAl_2O_4 + 2Na_2Si_3O_7,$$

accompanied by the entry of $CaAl_2O_4$ into solid solution in nepheline, is consistent with the intrusion of the melilite field into the lower subsidiary tetrahedron, nepheline-pseudowollastonite-anorthite-albite.

On the basis of these considerations it thus appears that the $Na_2Si_3O_7$ is the molecule in solid solution in gehlenite crystallizing in this system, and presumably one of the molecules in natural melilites also.

PETROLOGIC SIGNIFICANCE

THE SODA-LIME-ALUMINA-SILICA SYSTEM

The equilibrium relations revealed in the present investigation afford a contribution to the knowledge of the relation within the main system—the quaternary system soda-lime-alumina-silica. Complete knowledge of the equilibrium relations in the parent-system is of importance in the understanding of the problems of igneous petrology. This is evident from the consideration of the quantitative importance of the four oxides in the composition of igneous rocks. An enumeration of minerals that consist of these four oxides alone may further demonstrate the petrologic importance of this system. Among these are quartz, plagioclase feldspars, nepheline, wollastonite, gehlenite, corundum, sillimanite, mullite, grossularite, larnite, and jadeite. Knowledge of the four oxides has importance also in a number of technological applications. Equilibrium relationships in this system contribute a wealth of data which are of service in glass technology and the manufacture of refractories and of Portland cement.

THE SYSTEM $CaSiO_3$-$Ca_2Al_2SiO_7$-$NaAlSiO_4$

Comparison with natural magmas.—The present study extends our knowledge of the stability fields of three of the mineral-forming compounds which appear in the main system. The system constitutes a face of the subsidiary double tetrahedron and gives information particularly concerning relations with other planes which have now been investigated (Bowen, 1945, p. 83; Goldsmith, 1947) in the interior of the tetrahedron. The synthetic melts within the plane here studied do not correspond exactly in composition to any natural magma. The closest approach is found in magmas which formed certain feldspar-free rocks of the alkaline clan, such as melilite-nephelinites, urtites, ijolites, nepheline- and melilite-basalts. All these rocks contain considerable amounts of pyroxene and a variety of accessory minerals. The natural melilites all contain greater or less amounts of magnesia and iron and thus differ from those produced in this system.

The difference in size of the stability fields of the system herein investigated has some bearing on the crystallization of a magma which approaches in composition the confines of this system. For over 60 per cent of the composition range of the system, melilite is the primary phase. Liquids containing as little as 9 per cent gehlenite yield melilite as the

initial phase. Thus the present system yields corroborative evidence as to the order of crystallization in magmas. It is known that the bulk of the lime content of the magma tends to form complex lime silicates to the exclusion of the simple lime silicate, wollastonite. Many cases might be cited to show that melilite starts its crystallization early in rocks, even in those in which it is only moderately abundant.

The investigation of this system has some bearing upon the question of the origin of alkaline rocks. Daly (1933, pp. 497–544) and Tilley and Harwood (1931) have stated that melilite, nepheline, and wollastonite, in some instances, have formed as a result of the contamination of a magma by assimilation of limestone. The endogenous hybrid zone demonstrates that the excess CaO derived from limestone reacts with diopside to yield the akermanite molecule of melilite, and with anorthite to yield the gehlenite molecule of melilite, together with wollastonite. The formation of gehlenite as a result of the desilicating action of nepheline on lime silicate has been demonstrated by Gummer (1943, p. 527) and is very similar to the reaction postulated by Bowen (1922) to explain the formation of melilite from augite by the action of residual alkaline liquid in alnoitic rocks. It is difficult to say which of these processes is dominant in nature.

The occurrence of pseudowollastonite or wollastonite as earliest crystals is very rare. A wollastonite urtite and a wollastonite ijolite in which wollastonite forms about 72 per cent of the rock have been described by O. H. Erdmannsdörffer (1935) from the East African Rift. The textural relation of the wollastonite indicated that it formed earlier than nepheline. Becker (in Allen, White, and Wright, 1906, p. 89) states that Tornebohm observed wollastonite as inclusions in nepheline, feldspar, and aegirite. However, in most of the occurrences, wollastonite does not appear as the first mineral to crystallize. In the melilite rocks of Scawt Hill (Tilley and Harwood, 1931), wollastonite is interstitial with respect to the large melilite crystals. It occurs as an accessory mineral in the ijolite of Kuusamo, Finland (Hackmann, 1899), and in many of the foyalites of Sekukuniland, South Africa (Shand, 1921, p. 133).

Significance of the solid solutions.—Rock-forming minerals, with the exception of quartz, are members of solid-solution series. Pure end-members of solid-solution series are rarely, if every, found in nature. The results of this investigation demonstrate again the great tendency of both gehlenite and nepheline to form solid solutions. The system reveals that pure nepheline cannot exist in the presence of the lime-bearing compounds, $CaSiO_3$ and $Ca_2Al_2SiO_7$. The reaction between $CaSiO_3$ and nepheline has been demonstrated by J. Spivak (1944, p. 50) in the system $CaSiO_3$-$NaAlSiO_4$-Na_2SiO_3 to yield some anorthite and sodium metasilicate; and a reaction between nepheline and gehlenite to produce anorthite and $CaSiO_3$ has also been suggested by Smalley (1947, p. 34). The indications of a reaction between gehlenite and nepheline to produce $CaAl_2O_4$ and $Na_2Si_2O_7$ encourages the belief that pure gehlenite cannot form in the presence of any soda-bearing compound, for $Na_2Si_2O_7$ enters into solid solution in gehlenite. It is just what is to be expected from the complexity of the composition of the natural mineral.

CONCENTRATION OF SODIUM SILICATES IN RESIDUAL LIQUIDS

The manner in which calcium aluminum silicates tend to react with sodium aluminum silicates has now been demon-

strated in a number of investigations of systems in the general quaternary system. The exact nature of these reactions in the liquid can, of course, only be surmised, but some indications are available from the kinds of crystals (solid solutions) that separate. Several of these reactions, some of them already mentioned, develop sodium silicates, and there is a tendency for these to be stored up in residual liquids during crystallization. The details of this relation have been discussed by Bowen (1945, p. 87). Such residual liquids may be the actual agents of production of nepheline-melilite rocks when limestone and magma interact.

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THE PETROGRAPHY OF ROCK PHOSPHATES[1]

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ABSTRACT

Need for more extensive application of thin-section petrography to study of sediments, especially rock phosphates, is emphasized. The petrographic microscope alone is inadequate for investigation of these rocks, and often it will be necessary for the petrographer to employ X-ray diffraction, qualitative microchemistry, and other special methods.

The mineralogy of rock phosphates is discussed in light of present limitations of knowledge of these minerals, and data are furnished on thirty-eight minerals that can occur in these rocks. A list of recently discredited species is also furnished, and several textures and microstructures are illustrated.

The geochemical and mineralogical data on rock phosphates are regrettably meager. Theories on the origin of some of the primary, sedimentary rock phosphates cannot progress beyond the realm of speculation until the conditions which bring about precipitation of varieties of apatite from sea water have been more thoroughly investigated by laboratory techniques. Data on the origin of some of the rock phosphates of aluminum and iron are somewhat more complete, but, even here, the paragenesis of the minerals is poorly known.

INTRODUCTION

With the exception of the monographic works of Cayeux (1916, 1939, 1941), studies on the rocks of Sweden by Hadding (1932), and a few less comprehensive works, including some excellent studies on the petrography of coals, sedimentary rocks have not received the attention they deserve through the application of thin-section techniques.[2] Despite their commercial utilization, economic importance, and wide geographic distribution, the study of rock phosphates in particular has been neglected by most petrographers. Consequently, the mineralogy and textures of these rocks are poorly understood and may be completely unfamiliar to many advanced students of petrography.

Numerous theories on origin of phosphatic rocks have appeared in the literature, but most of these can be dismissed as inadequate because they were not predicated upon thorough petrographic study of the rocks under consideration but were based almost exclusively on inadequate field observations. In most cases the origin of rock phosphates will not be thoroughly understood until adequate petrographic data are available.

The role of carbon dioxide in the primary precipitation of calcium phosphate as a variety of apatite from sea water has been disregarded by most investigators. Kazakov (1937) has emphasized its importance, but his work seems to be unfamiliar to most American sedimentologists who have studied phosphate rocks in recent years. It is rather meaningless to attempt intricate calculations on the solubility of hydroxy-apatite or carbonate hydroxy-apatite or their fluorine-bearing analogues until the conditions which bring about their precipitation from sea water have been investigated adequately by experimental methods. For numerous reasons, then, the petrology of primary, sedimentary, rock phosphates will not be fully understood until the physical chemistry of this complex aqueous system has been studied in greater detail. Continuation and extension of the type of experiments conducted by Rivière (1941) will greatly aid in

[1] Manuscript received March 1, 1949.

[2] Shortly after the preparation of this manuscript an excellent general work on sedimentary rocks appeared (Pettijohn, 1949).

clarifying the role of carbon dioxide in precipitation of phosphates.

Cayeux (1936) has considered the extraction of phosphates from sea water by microörganisms and believes their contribution to be significant. Furthermore, Cayeux (1934) has concluded that some of the phosphatic nodules of the Agulhas Bank were not formed at depths from which they were dredged but accumulated there as a result of submarine erosion of materials formed at greater depths. These conclusions, based upon more complete study of the nodules, differ from earlier conclusions of Collet (1905). Similar studies of phosphatic nodules, dredged from submarine canyons off southern California, have been made by Dietz *et al.* (1942).

Among the general discussions that have appeared in recent years, one by Hutchinson (1944) and another by Mansfield (1940) are particularly noteworthy. Many valuable data obtained prior to 1933 are contained in the work of Jacob *et al.* (1933). However, in this brief discussion, the writer does not propose to present a critical review of the extensive literature on rock phosphates but merely to outline some of the petrologic interpretations that are dependent upon the petrographic data.

Thus, although the petrology of the rock phosphates will not be deduced from the petrography of these rocks alone, it seems worth while to summarize some of the data that have accumulated during recent years. By presentation of these results, it is hoped that interest will be stimulated and petrographers will direct further attention toward nonclastic sediments, particularly rock phosphates.[3]

[3] Some rock phosphates are not sedimentary but represent low-temperature metasomatic products of sedimentary, igneous, or metamorphic rocks. Nevertheless, they constitute a group which is closely related mineralogically.

METHODS OF INVESTIGATION

The usual microscopic methods are inadequate for thorough investigation of rock phosphates, not only because the common mineral species are likely to be microcrystalline, but also because they may display a significant range in optical properties due to isomorphic variations in composition. The problem is further complicated by the occurrence of various silicates, sulfides, oxides, organic matter, etc., in intimate association with the phosphatic minerals.

Sometimes it is necessary to obtain fairly complete separation of different mineralogical components and to apply special methods of investigation to the components thus isolated. X-ray diffraction methods are almost indispensable to an attack on these rocks, and qualitative microchemical determinations are usually helpful. In some cases it is possible to determine the principal mineral constituents of rock phosphates without difficulty, especially those consisting essentially of only one, two, or three minerals. On the other hand, identification of a minor constituent may be quite impossible by microscopic methods alone and may remain difficult even after a small purified sample has been isolated and studied by X-ray diffraction methods. These difficulties arise because only a few of the diffraction patterns have appeared in the literature.

Reliable chemical data may be extremely valuable and, in some cases, are indispensable. Unreliable chemical data, however, are worse than useless and can lead to some very unusual and erroneous conclusions.[4]

[4] For example, a paper (Burt, 1932) concluded that phosphate concretions from Brazos County, Tex., contained more than 50 per cent of "amorphous and colloidal alumina" on the basis of unreliable chemical data. A reliable determination of the aluminum made on a composite sample by

Rock phosphates, of course, cannot be analyzed by the methods ordinarily employed for silicate or carbonate rocks but require special methods outlined by Hoffman and Lundell (1938). Spectroscopic examination for heavy metals, particularly rare earths and vanadium, is part of a thorough geochemical investigation, as is also a determination of radioactivity.

The organic matter associated with certain types of rock phosphates has not been adequately investigated, and it seems probable that its extraction and identification will be difficult.

ROCK PHOSPHATES OF CALCIUM

Recently Bushinski (1945) has published a generalized classification of phosphorites in which he tabulated examples of marine, continental, and reworked deposits. He has indicated what is believed to be the principal phosphatic constituent for each of the deposits, and all minerals specifically mentioned were varieties of apatite, such as collophane, dahllite, fluor-apatite, hydroxy-apatite and oxy-apatite. This implies that Bushinski employs the term "phosphorite" in the same sense as Rogers (1944) and means a rock composed essentially of a variety of apatite.

Other calcium-phosphate minerals, including whitlockite, monetite, and brushite, have been found to occur in insular rock phosphates by Frondel (1943), and it seems probable that whitlockite may have been overlooked or misidentified in earlier investigations even though it may have been the principal constituent of other rock phosphates of calcium.

If the term "phosphorite" is restricted in such a way as to exclude all calcium phosphates other than varieties of apatite, it becomes virtually synonymous with collophane because the latter is not a mineral name in the strict sense, as pointed out by Frondel (1943, p. 220) and somewhat earlier by McConnell (1942, p. 656). It is suggested, therefore, that collophane be used to denote a natural, microcrystalline, phosphatic material that produces an X-ray pattern similar to apatite if it has not been investigated with sufficient thoroughness or if it is too impure to justify a specific name, such as dahllite, dehrnite, or francolite. It is also proposed that the term "phosphorite" be extended to include all rock phosphates of calcium whether or not they are composed essentially of varieties of apatite.

Rocks composed essentially of calcium-phosphate minerals may be comparatively free from other contaminating minerals and may display well-developed, agate-like banding (pl. 1, *A*). In

methods applicable to phosphatic materials indicated merely 7.4 per cent, rather than 57.5 per cent Al_2O_3, in the core of these concretions. X-ray diffraction studies furnished no evidence of the presence of aluminum oxides or hydroxides. The small amount of alumina probably occurs in the clay contained in the collophane (pl. 1, *D*). The absence of minor amounts of aluminum-bearing phosphate minerals could not be proved although none was detected.

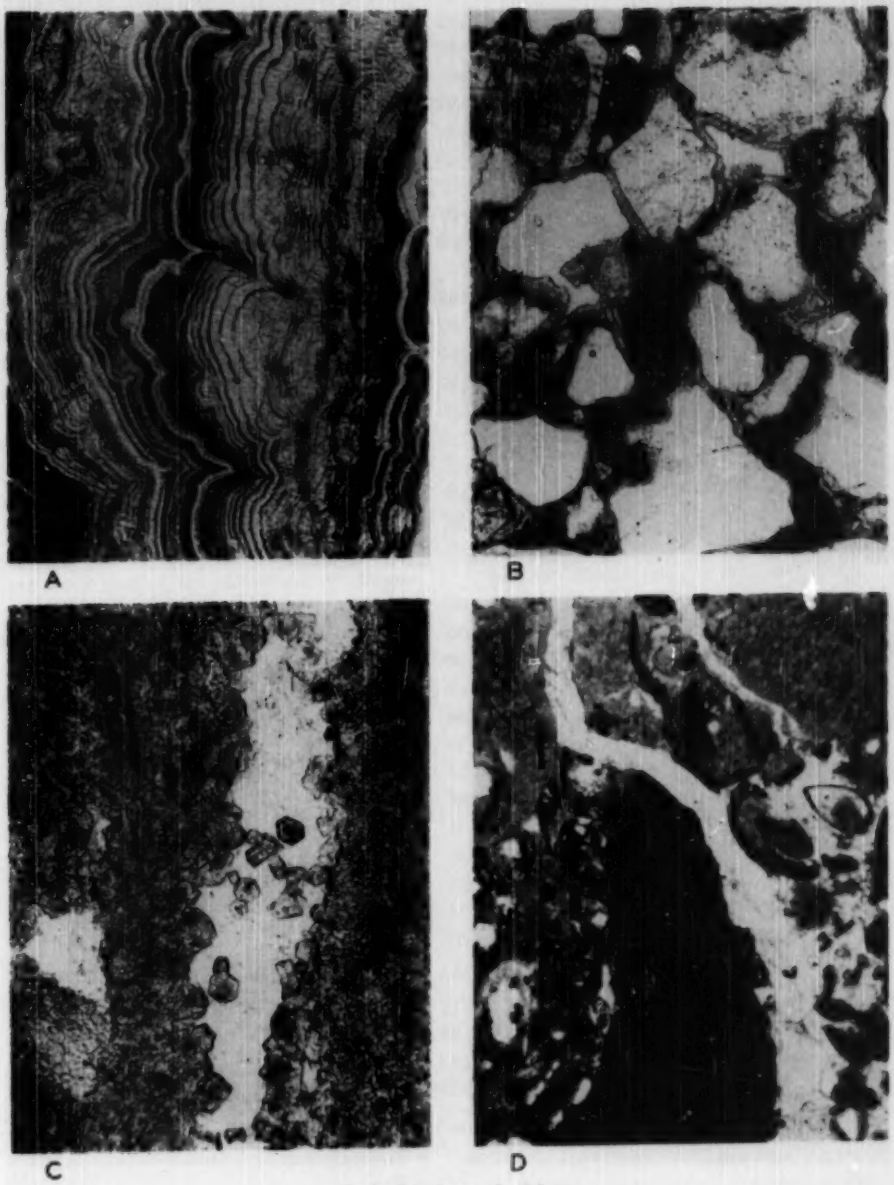
PLATE 1

A, Agate-like banding in dahllite (so-called quercyite) from Castillo de Belmez, Spain. The fibrous to flamboyant crystals are approximately normal to the bands. Dark portions are cloudy due to presence of submicroscopic inclusions. Magnification 44×.

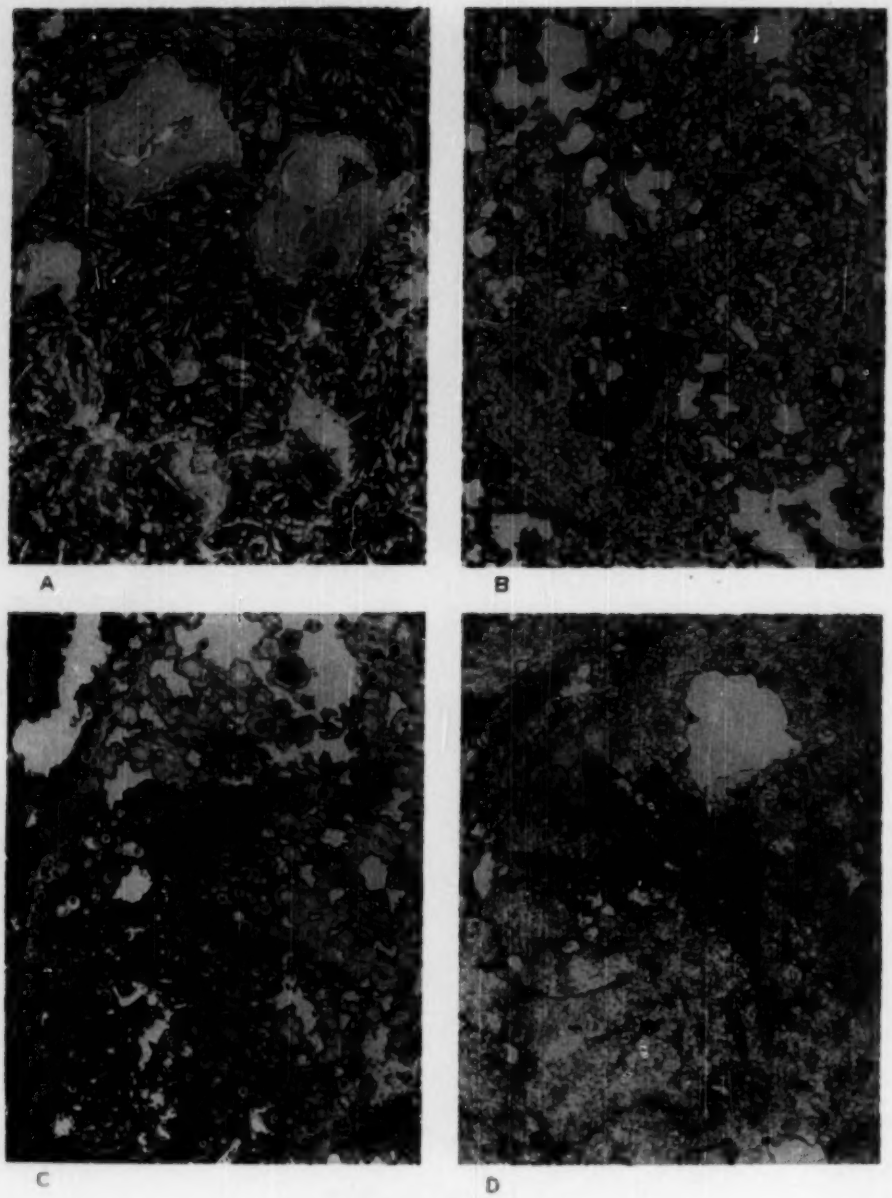
B, Sandy phosphorite from Kursk (so-called kurskite). The calcium-phosphate minerals form both isotropic and anisotropic crystalline cement for the glauconitic sandstone. Magnification 77×.

C, Phosphatic concretion from Podolia showing euhedral crystals of a variety of apatite within a matrix of quartz. These concretions also contain glauconite, pyrite, etc. Magnification 77×.

D, Phosphatic concretion from Brazos County, Texas. The large dark object is an appendage of a fossil crab which has been truncated by a calcite vein. The concretion is essentially collophane. It contains glauconite, quartz, limonite, pyrite, gypsum, etc. Magnification 30×.



Rock phosphates of calcium



Rock phosphates of iron and aluminum

some rocks, on the other hand, the principal phosphatic constituent forms a secondary cement for an assemblage of detrital minerals (pl. 1, *B*), or the phosphatic constituent is intimately intermixed with other constituents of complex concretions (pl. 1, *C* and *D*).

A black "oölitic" variety of phosphorite, which occurs in the Phosphoria formation of Idaho, is composed of small, fairly uniform, almost spherical nodules. In thin sections of standard thickness these small nodules are almost opaque because of contamination of the collophane by organic matter. Commonly these nodules occur in a matrix of colorless calcite, and, in some cases, the calcite transgresses the collophane nodules as small veinlets.

Varieties of apatite are known to replace wood (Simpson, 1912) with excellent retention of the structure of the organic material, and this fact suggests that the relict microstructures of varieties of apatite may be extremely diverse. Rogers (1924) demonstrated that most fossil teeth and bones are composed primarily of a variety of apatite, and, more recently, conodonts were found to have essentially the same composition by Stauffer (1938) and Ellison (1944).

ROCK PHOSPHATES OF IRON AND ALUMINUM

Our knowledge of the mineralogy and petrography of the rocks composed essentially of phosphatic minerals containing iron and aluminum is even less complete than our knowledge of the phosphorites. Most of the deposits which have been investigated thoroughly in recent years, however, have been found to be fairly simple in mineral composition. Their textures, although diverse, do not display the seemingly infinite variety found among the phosphorites.

Many of these deposits apparently originate from phosphatization of igneous rocks, and relict igneous structures and minerals may persist (pl. 2, *A* and *B*). Secondary spherulitic microstructures sometimes form in these deposits (pl. 2, *C*). Relict organic structures (pl. 2, *D*) may be found in rock phosphates if fossil-bearing strata have been phosphatized. This situation, however, is more common among the phosphorites.

The chief phosphatic constituent may be restricted to an orthorhombic or monoclinic member of the isodimorphous series: variscite-barrandite-strengite and metavariscite- clinobarrandite- phosphosiderite. This dimorphous series has been studied in some detail by X-ray diffraction methods (McConnell, 1940), and it has been found possible to estimate the iron-to-aluminum ratio from the dimensions of the unit cell. It is likely that the orthorhombic and monoclinic pair will be found together as an intimate mixture of microcrystalline substance (McConnell, 1943).

PLATE 2

A, Phosphatized amygdaloid from Malpelo Island, D.F., Colombia. Some of the amygdules and some of the lathlike crystals of the mesostasis are phosphates. Other amygdules of the same rock are opal; still others are mixtures. Magnification 38×.

B, Rock phosphate from Malpelo Island, D.F., Colombia. The porous phosphate is essentially a mixture of strengite and phosphosiderite, containing relict oxides of the original igneous rock from which it formed. Magnification 38×.

C, Rock phosphate from Gran Roque, D.F., Venezuela. The clear spherulites are composed of barrandite, whereas the cloudy portions are a mixture of microcrystalline barrandite and a variety of apatite. Magnification 26×.

D, Rock phosphate from the Connétable Islands, French Guiana. The aluminum-phosphate rock contains grains of residual quartz and relict organic structures. Magnification 26×.

TABLE 1

PHOSPHATE MINERALS LIKELY TO OCCUR IN ROCK PHOSPHATES

Mineral	Composition	Remarks and References
Francolite	Carbonate fluor-apatite	Very common (Deans, 1938; DeVilliers, 1942; Hutton and Seelye, 1942; McConnell, 1938*a*; Sandell, Hey, and McConnell, 1939)
Dahllite	Carbonate hydroxy-apatite	Fairly common (McConnell, 1938*a*, 1938*b*)
Brushite	$CaHPO_4 \cdot 2H_2O$	Occurs in insular deposits (Frondel, 1943; Mélon and Dallemagne, 1945; Prien and Frondel, 1947)
Monetite	$CaHPO_4$	Occurs in insular deposits (Frondel, 1943; Prien and Frondel, 1947)
Whitlockite	β-$Ca_3(PO_4)_2$	Occurs in insular deposits (Bannister, 1947; Frondel, 1941, 1943)
Pseudowavellite	$CaAl_2(PO_4)_2(OH)_2 \cdot H_2O$	Probably not rare (Larsen, 1942; McConnell, 1942)
Deltaite	$Ca_3Al_2(PO_4)_2(OH)_4 \cdot H_2O$	Probably rare (Larsen, 1942)
Dennisonite	$Ca_3Al(PO_4)_2(OH)_2 \cdot H_2O$	Probably rare (Larsen, 1942)
Overite	$Ca_3Al_2(PO_4)_2(OH)_6 \cdot 15H_2O$	Probably rare (Larsen, 1940, 1942)
Montgomeryite	$Ca_3Al_2(PO_4)_2(OH)_6 \cdot 11H_2O$	Probably rare (Larsen, 1940, 1942)
Sterrettite	$Al_2(PO_4)_2(OH)_6 \cdot 5H_2O$	Probably rare (Bannister, 1941; Larsen, 1942)
Variscite	$AlPO_4 \cdot 2H_2O$	Fairly common (Larsen, 1942; McConnell, 1940)
Metavariscite	$AlPO_4 \cdot 2H_2O$	Fairly common (McConnell, 1940)
Wavellite	$Al_3(PO_4)_2(OH, F)_3 \cdot 5H_2O$	Fairly common (Gordon, 1949)
Barrandite	$(Al, Fe)PO_4 \cdot 2H_2O$	Common (Gordon, 1925; McConnell, 1940)
Clinobarrandite	$(Al, Fe)PO_4 \cdot 2H_2O$	Probably common (McConnell, 1940)
Strengite	$FePO_4 \cdot 2H_2O$	Probably rare (McConnell, 1940, 1943)
Phosphosiderite	$FePO_4 \cdot 2H_2O$	Probably rare (McConnell, 1939, 1940, 1943)
Vivianite	$Fe_3(PO_4)_2 \cdot 8H_2O$	Probably fairly rare (Barth, 1937; Hutton, 1941)
Cacoxenite	$Fe_4(PO_4)_3(OH)_3 \cdot 12\frac{1}{2}H_2O$	Probably fairly rare (Gordon, 1949)
Dufrenite	$Fe_2PO_4(OH)_2$	Probably not rare (LeMesurier, 1943; Simpson, 1912)
Beraunite	$Fe_5(PO_4)_4(OH)_5 \cdot 2\frac{1}{2}H_2O$	Probably rare (Gordon, 1925; LeMesurier, 1943)
Bobierrite	$Mg_3(PO_4)_2 \cdot 8H_2O$	Probably rare (Barth, 1937; Gruner and Stauffer, 1943; Hutton, 1941; Prien and Frondel, 1947)
Newberyite	$MgHPO_4 \cdot 3H_2O$	Probably rare
Collinsite	$Ca_2(Mg, Fe)(PO_4)_2 \cdot 2H_2O$	Probably rare (Poitevin, 1927; Wolfe, 1940)
Stercorite	$NH_4NaHPO_4 \cdot 4H_2O$	Probably very rare
Struvite	$NH_4MgPO_4 \cdot 6H_2O$	Probably rare (Hutton, 1945; Prien and Frondel, 1947)
Turquoise	$CuAl_6(PO_4)_4(OH)_8 \cdot 5H_2O$	Fairly common (Graham, 1948)
Taranakite	$K(Al, Fe)_3(PO_4)_3(OH) \cdot 9H_2O$	Probably rare (Bannister and Hutchinson, 1947)
Minyulite	$K_2Al_4(PO_4)_4(OH, F)_2 \cdot 8H_2O$	Probably rare (Simpson and LeMesurier, 1933; Spencer, Bannister, Hey, and Bennett, 1943)
Anapaite	$Ca_2Fe(PO_4)_2 \cdot 4H_2O$	Probably rare (Wolfe, 1940)
Englishite	$Ca_4K_2Al_8(PO_4)_8(OH)_{18} \cdot 9H_2O$	Probably very rare (Larsen, 1942)
Wardite	$CaNa_4Al_{12}(PO_4)_8(OH)_{18} \cdot 6H_2O$	Probably very rare (Larsen, 1942; Pough, 1937*b*)
Millisite	$Ca_2(Na, K)Al_{12}(PO_4)_8(OH)_{18} \cdot 6H_2O$	Probably very rare (Larsen, 1942)
Lehiite	$Ca_2Na_2Al_8(PO_4)_8(OH)_{14} \cdot 6H_2O$	Probably very rare (Larsen, 1942)
Gordonite	$MgAl_2(PO_4)_2(OH)_2 \cdot 8H_2O$	Probably very rare (Larsen, 1942; Pough, 1937*a*)
Dehrnite	Na-bearing variety of apatite	Probably rare (McConnell, 1938*a*)
Lewistonite	K-bearing variety of apatite	Probably rare (McConnell, 1938*a*)

Varieties of apatite may occur in association with iron-aluminum phosphates (McConnell, 1941), and secondary silica or silicates may occur as a result of incomplete leaching of the igneous rock by the phosphatizing solutions.

The mineralogy of secondary phosphate deposits may be extremely complex, as was found to be true of the nodular deposits near Fairfield, Utah, by E. S. Larsen III (1942). Gordon (1925) identified variscite, barrandite, strengite, wavellite, beraunite, and cacoxenite in the secondary deposits at Moore's Mill, Cumberland County, Pennsylvania. The separation and identification of microcrystalline aggregations of such minerals may be extremely difficult for reasons already mentioned.

TABLE 2

DISCREDITED NAMES FORMERLY APPLIED TO PHOSPHATE SUBSTANCES

Mineral	Reference
Callainite	McConnell (1942)
Coeruleolactite	McConnell (1942)
Eggonite	Bannister (1941)
Epiglaubite	Frondel (1943)
Glaubapatite	Frondel (1943)
Kurskite	McConnell (1938*a*)
Lucinite	Gordon (1925); McConnell (1940)
Martinite	Frondel (1943)
Messelite	Wolfe (1940)
Metabrushite	Frondel (1943)
Minervite	Bannister and Hutchinson (1947)
Monite	Frondel (1943); Strunz (1939)
Nauruite	Frondel (1943)
Ornithite	Frondel (1943)
Palmerite	Bannister and Hutchinson (1947)
Peganite	Gordon (1925); McConnell (1940)
Pyroclasite	Frondel (1943)
Pyroguanite	Frondel (1943)
Pyrophosphorite	Frondel (1943)
Quercyite	McConnell (1938*a*)
Redondite	McConnell (1940)*
Sombrerite	Frondel (1943)†
Staffelite	Sandell, Hey and, McConnell (1939)
Stoffertite	Frondel (1943)
Zepharovichite	McConnell (1942)
Zeugite	Frondel (1943); Strunz (1939)

* Recent X-ray investigations by the writer indicate that "Redondite, Redonda, West Indies," is a mixture of barrandite and clinobarrandite. The sample was obtained from Columbia University and may be a portion of the type material to which C. U. Shepard applied the name.

† Recent unpublished results obtained by the writer confirm Frondel's results and indicate that the rock phosphate from Sombrero Island is essentially a variety of apatite.

MINERALOGY OF THE ROCK PHOSPHATES

The older literature on the mineralogy of rock phosphates and phosphorites is unreliable because many of the original descriptions of the minerals were inadequate according to modern standards. This fact has necessitated re-examination of numerous samples by modern methods. As a result of restudy some mineral names have already been discarded, and others will undoubtedly follow.

From the paragenesis of rock phosphates that have been studied and from a knowledge of the temperatures and environmental conditions which permit crystallization of the various phosphate minerals, it is, however, possible to compile a list of minerals that are likely to occur. Such a list of minerals, together with their compositions, is given in table 1. Remarks on occurrence and references to recent works are also given. Doubtful species have been omitted from the table.

It seems appropriate to furnish a list of mineral names that have been discredited or discarded inasmuch as these names occasionally appear in recent literature, despite the fact that they have

no standing among mineralogists. These names are given in table 2, in each instance with a reference to recent work.

CONCLUSIONS

The petrographic, geochemical, and mineralogical data on rock phosphates are regrettably meager. Comprehensive statements on the paragenesis of these rocks are not justifiable in view of limitations of present knowledge concerning their constituent minerals.

Much of the early work on the mineralogy of rock phosphates is confused by the application of mineral names to mixtures of minerals. Whenever possible, type material should be re-examined in order to eliminate this confusion. This work will require the use of X-ray diffraction methods in addition to usual microscopic and chemical techniques.

Only after paleontological, petrographic, and geochemical data have been reconciled will it be possible to postulate valid conclusions concerning the origin of some of the sedimentary rock phosphates. Other types, which originate from the action of solutions from guano on pre-existing rocks, may have simpler histories, but, even here, interpretations are difficult because of the inadequacy of the data.

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RIPPLE MARK IN ROCK SALT OF THE SALINA FORMATION[1]

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ABSTRACT

Extensive series of ripple mark at various horizons have been observed in Silurian rock salt of the Salina formation. Anhydrite lamellae which show similar ripple mark have been observed in the clear salt mass. These are the first large-scale observation of ripple mark in rock salt. The only other published observation was made in 1908 on small ripples in a rock-salt drill core of Permian age from the Zechstein in Hesse.

This paper describes ripple mark and negative (mold) of ripple mark observed on an extensive scale in the Detroit Mine of International Salt Company, Incorporated, in the Silurian rock salt of the Salina formation of Michigan. The geological section of this mine has been described by Fay (1911), Sherzer (1911), and Vanderwilt (1923).

Zimmerman (1908) has described small ripples in rock salt of Permian age in a drill core from the Zechstein in Hesse. Ripple mark in the Salina formation was first observed in 1933 by one of us, who carried on occasional field work until 1937.

A feature to be emphasized before discussing the ripple mark is the varvelike stratification of the salt beds, a feature which is found not only in the seam which is mined but also in salt beds above and below the present mining operations. Plate 1, *A*, shows a typical face. Each of the individual stratification bands is very persistent throughout the entire mine, showing only minor variations of spacing or intensity.

Although the bands range from an almost imperceptible brown tint to dark brown or black, in no case do the layers appear to the eye as pronounced as in the photograph, for the camera accentuates the darkness and sharpness of the bands. Shading gradually into the white salt, above and below, they defy accurate measurement and can only be described as relatively narrow or relatively broad. To the eye, freshly broken bands reveal a texture and composition like that of the whiter salt between them.

If the face of the salt is sprayed with water and slowly dissolved away, the core of the dark bands begins to protrude. This core consists of either a single layer or several layers of paper-thin lamellae of white or gray anhydrite, separated by narrow zones of salt of variable thickness. The lamellae are in some cases crowded so close together as to be almost indistinguishable. A group of four or five may occur in a centimeter of vertical distance; one or several such groups may make up a single dark band; or but one or two lamellae may occur within a dark band. In a few instances anhydrite

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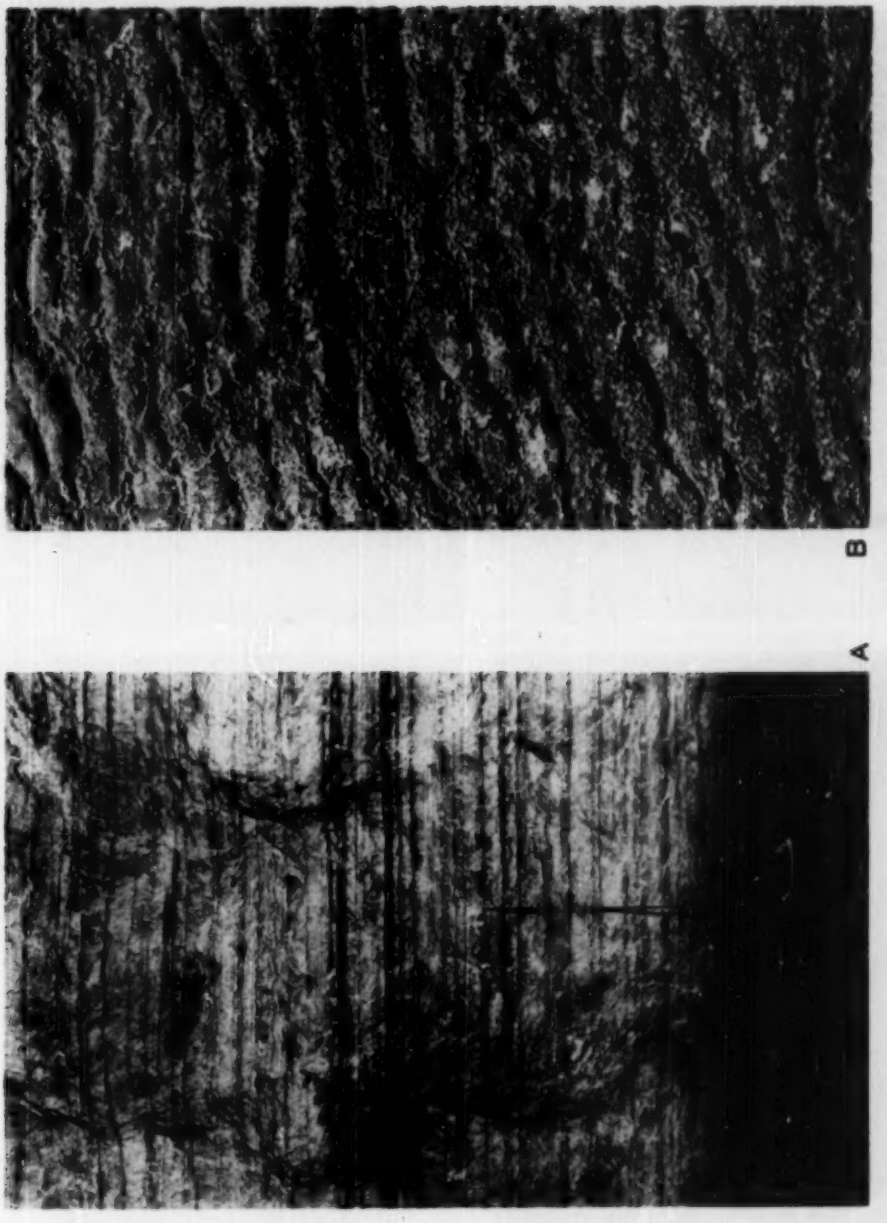
PLATE 1

A, Typical face of rock salt showing stratification bands which are accentuated in the flashlight photograph. A 6-foot rule leans against the wall. The apparent curving of the bands is due to irregularities in the salt face.

B, Mold of ripple series No. 6.



B

A

Ripple marks and molds in rock salt

Ripple marks and molds in rock salt

lamellae were locally as thick as $\frac{1}{16}$ inch. The clear thick bands of white salt between the darker layers commonly contain these same thin lamellae of anhydrite, but these are not observable until solution causes the edges of the anhydrite to project from the surface.

In the past there has been speculation as to whether the dark bands were markers of seasonal, climatic, or some other type of environmental change. The presence of the possibly unsuspected anhydrite lamellae in the main mass of light-colored salt as well as in the dark bands indicates that the environmental changes were much more frequent than would be suggested by the dark bands alone—possibly annual. Furthermore, the presence of several lamellae and groups of lamellae in a single dark band possibly indicates cyclic disturbances lasting over several years.

There is no regularity whatever in the vertical spacings between the dark bands. The bands are horizontal; and, although in places two or three may separate or converge for a short distance, the relative spacings between the bands below and above such apparent irregularities remain uniform.

There seems to be but little tendency for the salt to split along the stratification planes when blasted in mining operations. However, the salt at the mine roof sometimes separates along these planes when the explosive is placed at a certain level, and the blasted salt drops toward the mine floor. Continuous parting along one of these planes, which has developed from such blasting operations, shows ripple mold over 1,000 square feet.

In addition to partings at the mine roof, there are localities where parting has occurred owing to such local circumstances as undercutting of the mine face which permitted part of the salt mass to drop down and away from the salt above owing to tension, in contrast to the directionless shattering effect from blasting. The effect of tension in the salt mass is to cause a clean, smooth separation at one of these stratification planes of natural weakness.

The partings thus developed by tension sometimes separate the lower and upper surfaces by as much as 2 feet. The ripple mark and mold described in this paper are found on some of these parting surfaces.

Ripple mark or cast is not found on every parting throughout the mine. It was first observed at a single mined-out locality where seven partings had developed at different horizons in the exposed face and roof areas. Ripple mark and/or cast was observed on every parting surface. Figure 1 shows the vertical relationship between the seven ripple horizons.

PLATE 2

A, Flashlight photograph of the mine roof showing the cast of ripple series No. 4; a composite ripple consisting of two independent series of ripples with an angle of 69° between the strike of the crests. At any given locality one series is more pronounced than the other. In the lower right corner the more pronounced crests run vertical to the page, while in the upper left-hand corner they cut diagonally across.

B, Ripple series No. 5. Slab of rock salt showing cast of interference ripple of the polygonal, cell-like type called "tadpole nests." A 6-inch rule is shown at the lower edge of the photograph.

C, Looking upward at the cast of ripple series No. 1 on the underside of ledge overhanging the bulletin board outside underground office. Since the face of the ledge has been painted, the stratification bands are not visible.

D, Flashlight photograph showing ripple series No. 1 in the face of the mine. The darker portions of the photograph do not represent stratigraphic features but are accumulated debris and stains on the surface of the rock salt.

Horizontally, all the observed parting surface edges were less than 50 feet, and in most cases less than 10 feet, apart. Thus, figure 1 shows a truly vertical series of ripple horizons.

The dark stratification bands extending uninterruptedly throughout the mine were used for correlation of two other ripple horizons (No. 2 and No. 3) with those noted in figure 1.

Ripple horizon No. 6 is by far the best developed, most uniform, and continuous horizon observed with ripples, shown in plate 1, *B*. Horizon No. 2 is 800 feet S 40° W of the series shown in figure 1 and by correlation is 5 inches above No. 1. Horizon No. 3 is 2,200 feet S 81° W of the series shown in figure 1 and by correlation is 7 inches above No. 2. Horizons Nos. 4 and 5 are examples of cross ripples with different crest distances, depths, and strikes (pl. 2, *A*). Horizon No. 5 is a magnificent example of the "tadpole nest," a type illustrated by plate 2, *B*.

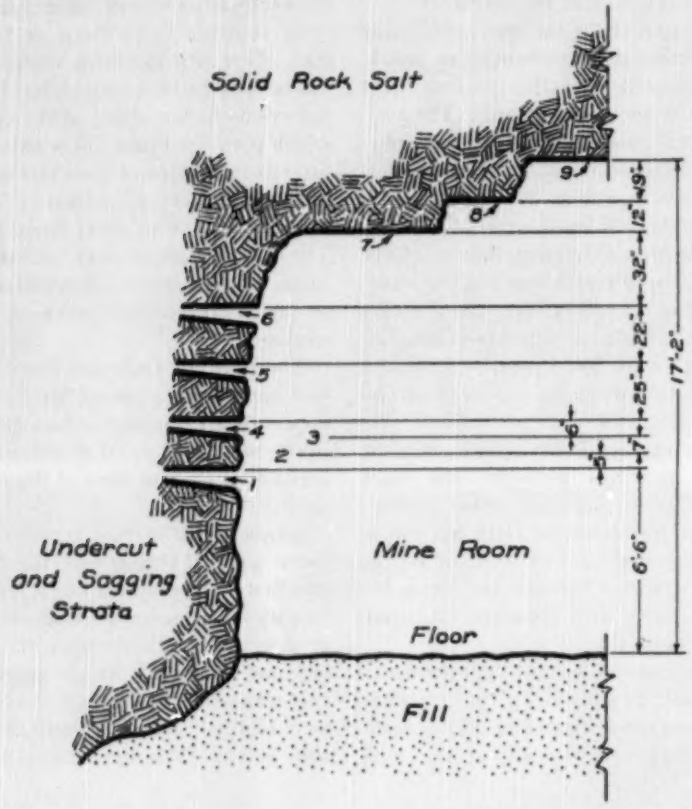


FIG. 1.—Vertical cross section at right angles to mine face showing partings in rock salt at ripple-mark horizons due to undercutting at mine floor and subsequent sagging of strata. Partings actually extend almost horizontally for several hundred feet to the left, instead of narrowing quickly as shown.

Table 1 gives the average crest distance, depth, strike of the crest, and the largest observed area of continuous ripple mark or cast for each series. Horizon No. 4 lists both sets of cross ripple mark.

The largest ripple mark observed was in one local area in horizon No. 1 where the crest distance was 13 inches and the depth $1\frac{3}{8}$ inches.

Horizon No. 1 in the series of ripple mark is illustrated in plate 2, *C*. The smoothness and the symmetry of these ripples as illustrated in the photograph are characteristic of this horizon, which can be traced continuously from pillar to pillar for approximately 1,000 feet from the locality of figure 1. Local variations may be found in this distance, with 6 inches the smallest distance from crest to crest and 13 inches the largest crest distance observed. As will be noted later, this horizon possesses many characteristics other than its size and continuity which differentiate it from the others.

Zimmerman (1908), Kindle (1917), and Twenhofel (1932) have emphasized the limitation of ripple mark to granular sediments with little or no cohesion between the particles. This lowermost of the observed ripple horizons is the only one where the material immediately underlying the ripple mark is sufficiently granular and unconsolidated that movement of its particles into crests and troughs by wave action may be considered. A unique feature of these ripples is the ease with which they can be traced along the mine walls by association with a clear layer of white salt immediately underlying the ripple-mark layer (pl. 2, *D*). The ripples are formed in this layer of fine granular, poorly coherent massive salt crystals which extends about 1 inch below the bottoms of the troughs and rests upon a brown stratification band merging into the densely crystalline massive rock salt below. The ripple counterpart forms a similar brown stratification band which merges upward into the same type of massive rock salt.

Laboratory examination shows this band of halite to be coarsely granular and friable, readily broken in the hand. It is nearly pure white and, because of cleavage faces of the halite crystals, resembles certain white crystalline marbles. When crumbled, it is seen to consist of clear glassy crystals ranging from $\frac{1}{2}$ to 5 millimeters in diameter. Some of the crystals retain their original cubical outline, while others show typical solution effects which give the crystals an irregular rounded glassy surface.

TABLE 1

Horizon Number	Average Crest Distance (Inches)	Average Depth (Inches)	Strike	Maximum Observed Area (Sq. Ft.)
9	3	$\frac{1}{4}$	N 60° E	2
8	3	$\frac{1}{4}$	N 60° E	15
7	3	$\frac{1}{4}$	N 45° E	7,500
6	7	$\frac{1}{4}$	N 45° E	900
5	5	$\frac{1}{4}$	Variable	37,500
4A	4$\frac{1}{2}$	$\frac{1}{4}$	N 7° E	6,600
4B	5$\frac{1}{2}$	$\frac{1}{4}$	N 62° W	
3	9	$\frac{1}{4}$	N 60° E	1,000
2	2$\frac{1}{2}$	$\frac{1}{4}$	N 40° E	72
1	8	$\frac{1}{4}$	N 45° E	36,000

Unlike the remainder of the mined rock salt, this granular halite is remarkably free from liquid inclusions and does not take up moisture under fairly humid laboratory conditions. On drying at 110° C. it loses only 0.02 per cent by weight. It fuses without decrepitation with a total loss of 0.03 per cent. Analysis shows it to contain 0.69 per cent of impurities consisting of anhydrite and calcite. When immersed in a liquid of the

same index of refraction as the halite (1.544), the inclusions within the halite crystals stand out in relief as flat euhedral crystals of anhydrite and minute rhombohedrons of calcite. No liquid inclusions were observed.

Because of the continuity, uniformity, and well-developed character of these ripples and the nature of the salt in which they were formed, the authors are of the opinion that they represent the development of ripples by wave action upon unconsolidated salt resting on a bed of consolidated salt. The uniformity of the entire rock-salt formation suggests that this action took place some distance from a shoreline. Drill records in this area reveal that one of the other salt seams in the Salina formation lying below the mine level thins rapidly to the northwest and indicate that a shoreline with a northeast-southwest trend existed along the northwest border of the mine at the time that the salt seam was deposited.

The existence of a layer of unconsolidated salt resting on bottom is not in accord with common observations of present-day salt deposition. It is significant that, with the exception of the lowermost series, the salt both above and below all ripple-mark partings appears massive and has firmly interlocking grains. In no other case was there observed a layer of clear friable salt in which the ripple could have been formed by particle movement. Neither do these other series show the continuity and uniformity observed in the lower horizon. In this connection there is a suggestion advanced by Walther (1912), who discusses the development of ripple in the salt basin of Mex. Walther describes the annual salt deposits as well stratified, with a coarsely crystalline texture of intergrown salt crystals forming a deposit "solid as ice." When the spring rains fall, the salt solution is diluted and the upper surface of the salt deposit redissolved. Since even a light wind produces a wave motion extending to the bottom in shallow water, the salt surface is dissolved into a series of troughs with intervening crests. If the mechanism noted by Walther is applied to the present case and dilution of the brine was caused by currents bringing in fresher water, wave action might result in the development of a ripple surface by solution, although the structures so developed might not properly be considered ripple mark. If the fresher waters carried calcium in solution, the formation of the thin lamellae of anhydrite could be due to interaction of the calcium with the sulphates or other salts in the older brine. The same type of reaction by the introduction of calcium salts might account for the numerous series of anhydrite lamellae which occur throughout the salt but which in general do not seem associated with ripple mark.

In describing ripple mark from the drill core in Hesse, Zimmerman (1908) speaks of various salt layers being separated by paper-thin layers of anhydrite. A pertinent feature of the anhydrite layers mentioned earlier in the present paper is that over a distance of a few feet it is often possible to observe a ripple profile in the anhydrite lamellae. As many as four of these thin layers have been observed within a vertical distance of 1 inch, each with its own undulatory profile. In some cases trough corresponds with trough and crest with crest, but more often each layer of a series has its own independent profile. The crests are always rounded. The maximum crest length observed was $2\frac{1}{2}$ inches and the maximum height $\frac{3}{8}$ inch.

In the general examination of the mine

the varvelike appearance of these anhydrite layers constantly impresses the observer. Whether they represent annual, seasonal, or other changes is a problem on which no light has been shed. The lack of literature on sedimentation from brine solutions has made the problems which have arisen difficult to answer. The authors feel, however, that the proved existence of ripple mark on a wide scale and at various horizons on rock salt may contribute to the knowledge of saline-deposit formation.

ACKNOWLEDGMENTS.—The writers wish to thank the officials of the International Salt Company, Incorporated, for the interest and co-operation which have made this paper possible.

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WOLF CREEK METEORITE CRATER, WESTERN AUSTRALIA[1]

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ABSTRACT

The Wolf Creek Crater is the second largest crater of meteoritic origin to be discovered on the earth's surface. The crater is circular, 2,800 feet in diameter, has a maximum depth of 170 feet and 90 feet of broken rock forming the elevated rim. Fragments of meteoritic iron were found around the rim. The age of the crater is considered to be Pleistocene or Recent.

INTRODUCTION

The Wolf Creek meteorite crater, situated in the Kimberley District of Western Australia, is the second largest crater of meteoritic origin to be discovered on the earth's surface. The crater has been named by Dr. Reeves (Reeves and Chalmers, 1948) after the adjacent watercourse, Wolf Creek.

The nature of the crater was first recognized on June 21, 1947, by Dr. Frank Reeves and N. B. Sauvé of the Vacuum Oil Company during an aerial reconnaissance of the Desert Basin in a Zinc Corporation aircraft piloted by Dudley Hart. It was reached on the ground on August 24, 1947, by Reeves, Harry Evans, and Dudley Hart.

The crater was independently located and its meteoritic origin suspected by the writers early in 1948 when preparing a photogeological map from photographs covering the area.

LOCATION AND DESCRIPTION

The crater is situated on the northern edge of the Desert Basin at approximately 127°46′ east, 19°18′ south, 65 miles south of Halls Creek, the nearest township and aerodrome.

The crater may be reached without difficulty during the dry season by taking the track from Halls Creek to Ruby Plains homestead and thence to Beaudesert Well. Near Beaudesert Well a branch track is followed along the west bank of Wolf Creek as far as the crater (fig. 1).

The crater is situated in an area covered with loose sand with occasional low dunes and sparse vegetation, a few miles south of the last observed outcrops of Nullagine quartzites and grits of pre-Cambrian age. Nullagine quartzites are exposed in the crater.

The crater, from the Beaudesert Well approach, appears as a low hill in an otherwise featureless area, and from a distance there is nothing to suggest the existence of the crater behind the rise. As the hill is approached, the piles of broken rock forming the rise are seen more clearly, and the peculiarities of the hill become more obvious.

The general appearance when viewed from the foot of the rise is unique. In particular, the massive pile of unsorted blocks of red-brown quartzite on the southerly flank of the crater rim is very striking. The view from the top of the rim is most imposing, and the perfection, that is to say, the symmetry and uneroded condition, of the crater must be seen to be believed.

The average depth of the crater below the rim is 160 feet, or an average depth

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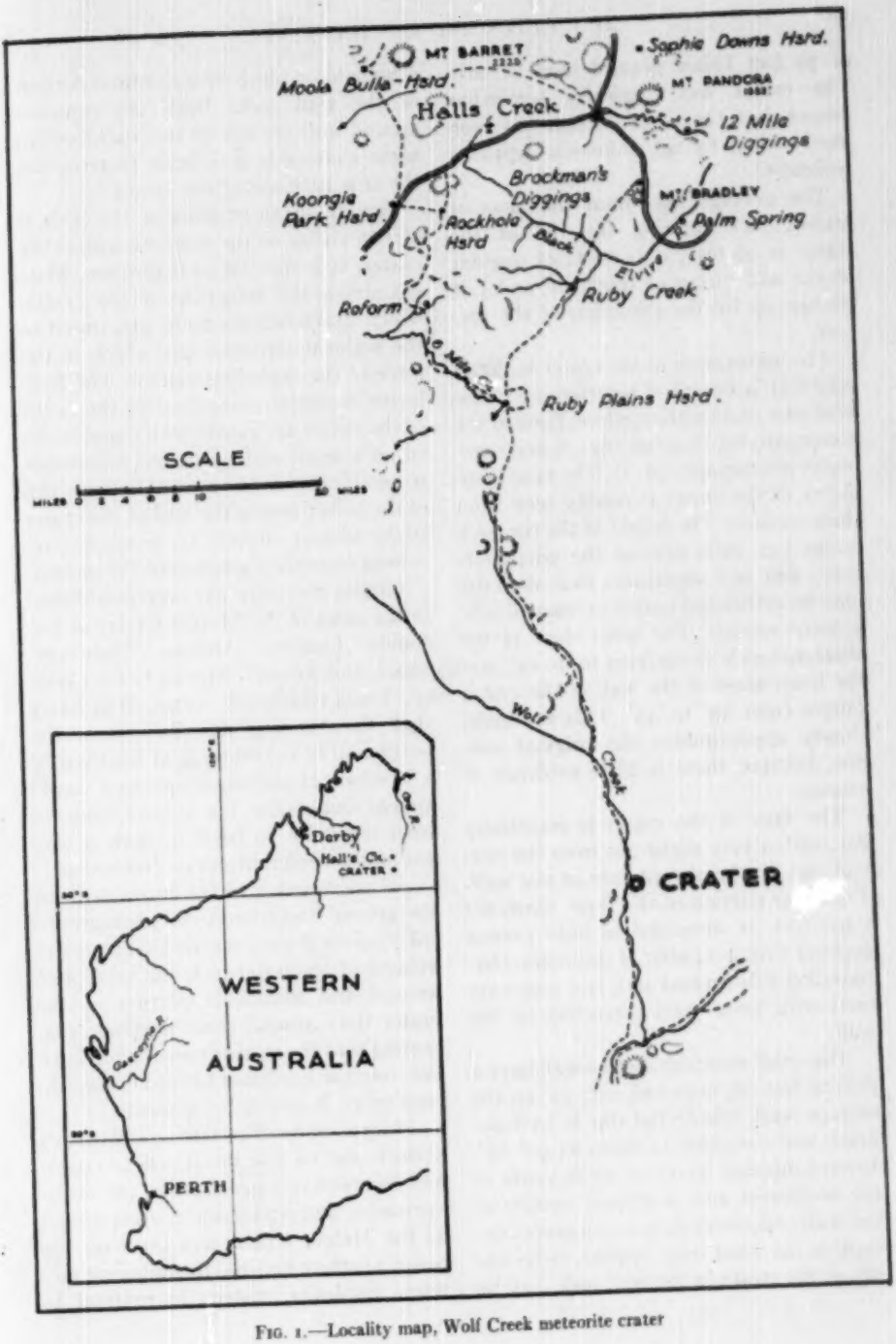


FIG. 1.—Locality map, Wolf Creek meteorite crater

of 70 feet below general land surface. The crater was originally somewhat deeper, but the inner portion has been partly filled by an unknown depth of sediment.

The average maximum thickness of broken rock forming the rim of the crater is 90 feet; it consists of angular blocks and pieces of quartzite and grit thrown up by the explosion of the meteor.

The appearance of the crater in detail may best be described by reference to the west-east and south-north sections in the accompanying diagram (fig. 2) and composite photograph (pl. 1). The near symmetry of the crater is readily seen from these sections. The height of the rim rock varies but little around the circumference, and any variations that do exist may be attributed partly at least to subsequent erosion. The outer slope of the shattered rock varies from 10° to 15°, and the inner slope of the wall of the crater ranges from 30° to 40°. This no doubt closely approximates the original outline, because there is little evidence of erosion.

The floor of the crater is essentially flat, with a very slight rise from the central area to the abrupt face of the wall. The inner portion of the floor, diameter 1,400 feet, is composed of light porous gypsum with a number of sinkholes. Surrounding this central area is a zone covered with loose sand extending to the wall.

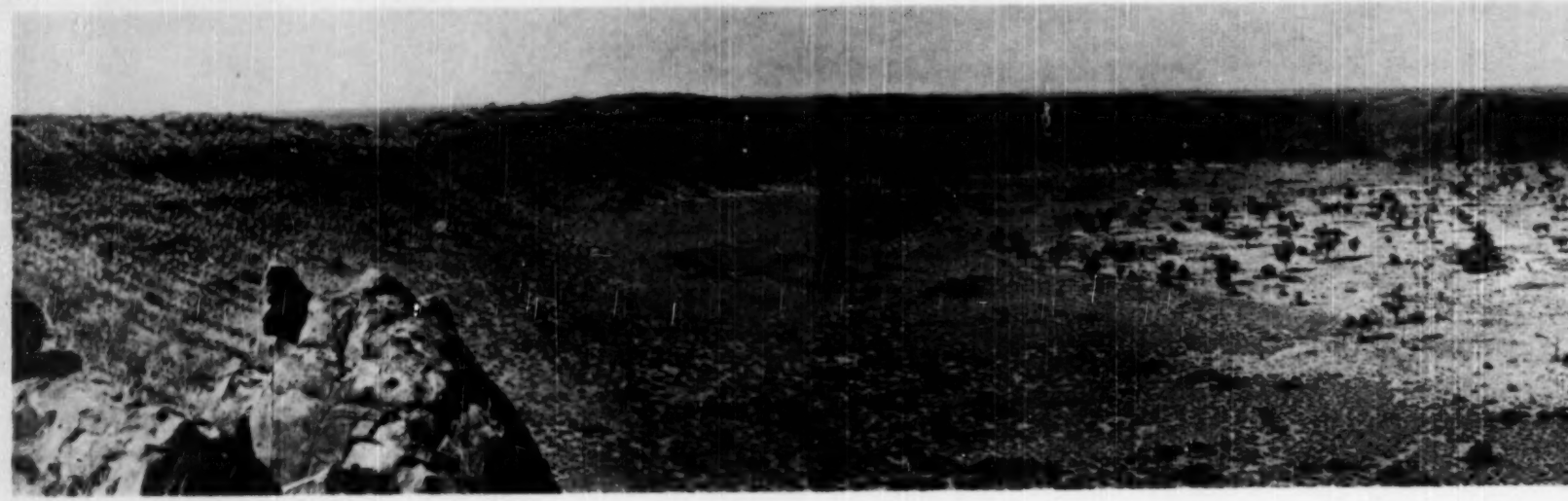
The quartzites forming the wall have a general low dip outward, e.g., 20° on the eastern wall, where the dip is well defined, and elsewhere as much as 50°–60°. Inward-dipping strata occur in parts of the southwest and northwest sectors of the wall. Apparent dips are in places deceptive, as what may appear to be the dip of the strata in the wall rock may be a large loose block or a slumped portion of the wall rock. Both are common around and on top of the wall, and in some sections it is difficult to recognize the true attitude of the strata.

A very sharp bending of the beds is clearly visible on the northern wall of the crater. It is difficult to determine, when examining the structure of the crater, which characters are to be attributed to the regional structure and which to the force of the exploding meteor. The Nullagine sediments examined to the north of the crater are gently folded and faulted on a small scale. It seems reasonable to postulate that the general outward dip of the beds forming the wall of the crater is due almost entirely to movement resulting from the explosion of the meteor.

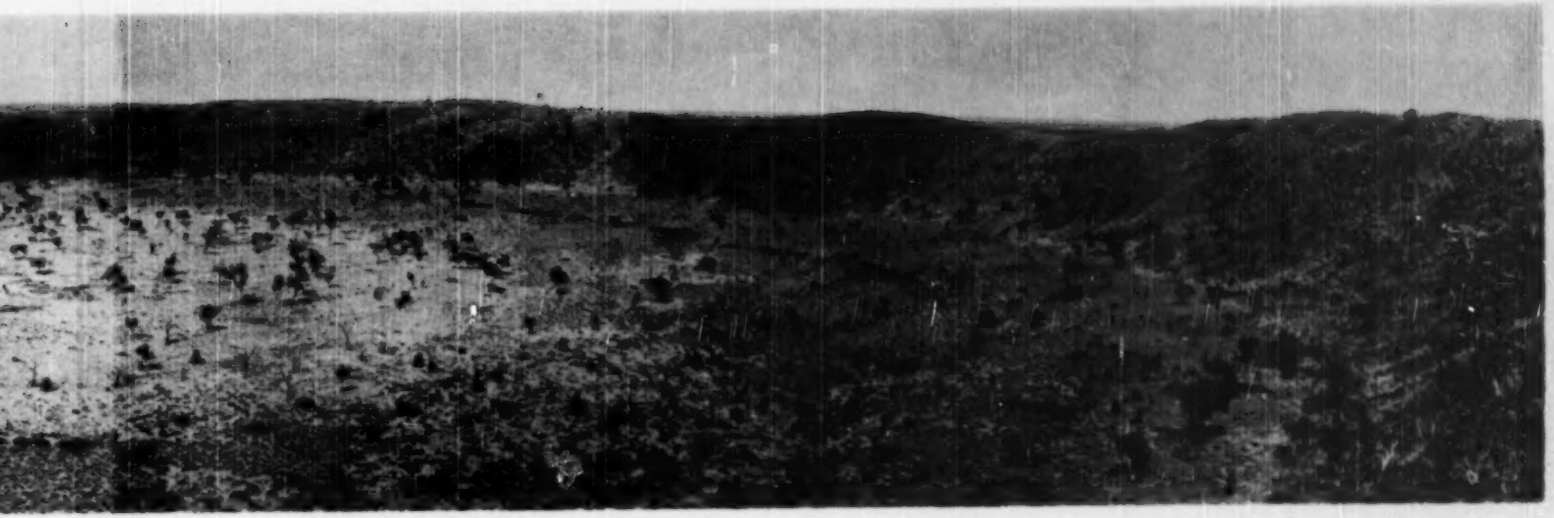
Similar structure has been established in the cases of the Meteor Crater of Coconino County, Arizona (Barringer, 1909), and Texas Crater in Ector County, Texas (Barringer, 1929). It is likely that the bending described from the north wall of the crater is at least partly a structure of premeteor age, as it would appear impossible for surface beds of hard quartzite to bend in such a way without considerably more fracturing.

An examination of the crater both on the ground and from aerial photographs (pl. 2) gives the impression that a greater volume of fractured rock has been piled around the southwest portion of the crater than around other portions, suggesting that the meteor was moving in an arc from the northeast toward the southwest when it struck the ground.

From a study of craters on the earth's surface and on the moon, Dietz (1946) and others have suggested that the radial symmetry and circularity of craters such as the Meteor Crater and those on the moon's surface are due to exploding meteors. Explosion craters, in contrast to



Interior of Wolf Creek meteorite



eorite crater, looking south

Aerial photograph of Wolf Creek meteorite crater

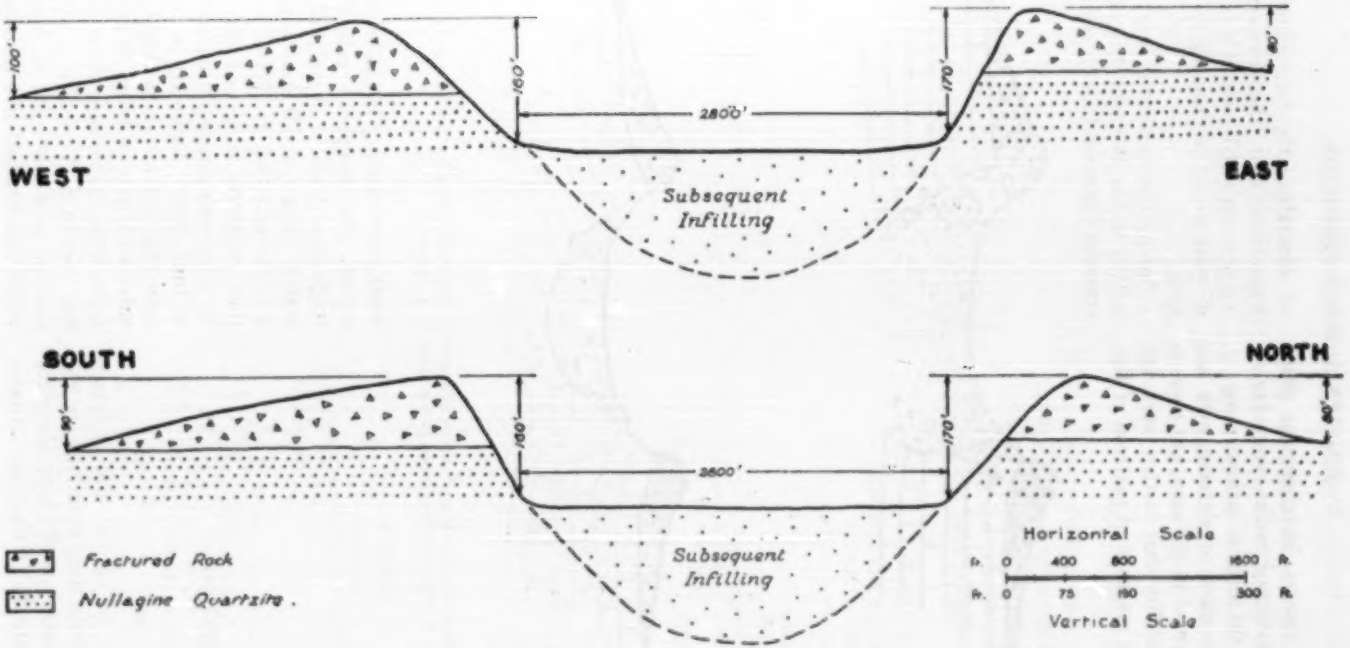


FIG. 2.—Cross sections of Wolf Creek meteorite crater

percussion craters, have circular shape and well-developed radial symmetry regardless of the angle of incidence (fig. 3).

No silica glass or sintered rock has been discovered in the area, but there is every probability that further work will disclose the presence of material of this character.

of minerals of the Australian Museum, has advised that "the specimen contains 1.9 per cent of NiO which is far in excess of what would be expected in terrestrial rock."

Samples of meteoritic iron were submitted to the Western Australian Government Chemical Laboratories. The following information is taken from their report. The samples consisted of two fragments, A and B. A weighed approximately 300 gm. and B approximately 500 gm. The material is sufficiently magnetic that fragments of pea size may be lifted by a bar magnet, and it consists mainly of iron oxides, hydrated in part, with some silicate minerals too highly impregnated with iron oxides to be identifiable, and a little chalcedony. After fine grinding, specimen A yielded a very small amount (0.06 per cent) of metallic iron which was retained on a 90-mesh screen.

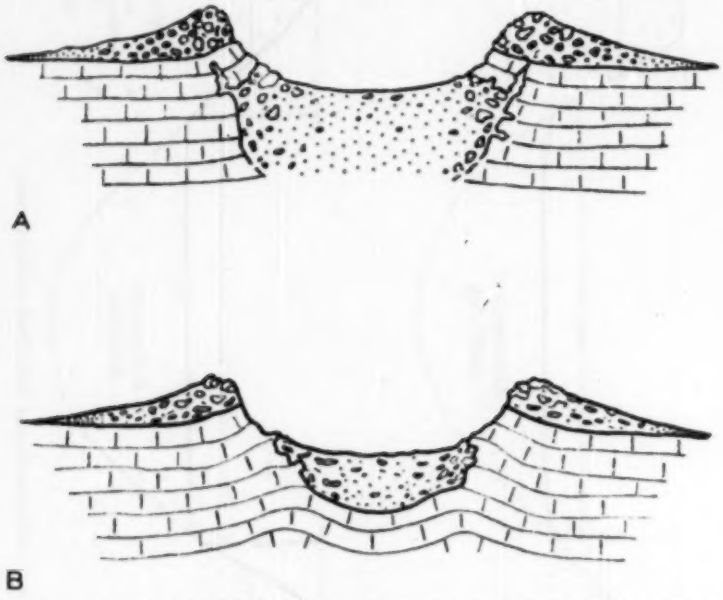


FIG. 3.—Diagrammatic sections of a typical meteorite crater. *A*, fracturing and tilting of strata by outward explosion; *B*, ring anticline by percussion (after L. J. Spencer).

TABLE 1

ANALYSIS

	PER CENT	
	A	B
Nickel, Ni in metallic portion	3.71	.....
Nickel, Ni total	3.57	4.47
Specific gravity	3.42	3.80

Fragments of various size of heavy metallic material were found around the rim of the crater, particularly along the southern sector. R. O. Chalmers, curator

GENERAL DISCUSSION

An interesting paper by Nininger (1948) covers the geological significance of meteorites. It took scientists many years to accept the fact that matter from outside the earth and its atmosphere was falling and had fallen on the earth's surface. Today there are still some who will not accept the meteoritic origin of some craters.

It is apparent that studies of craters such as the Meteor Crater, Arizona (Barringer, 1909, 1915, 1925), Boxhole Crater, Central Australia (Madigan, 1937), Texas Crater (Sellards, 1927; Barringer, 1929), Henbury Craters (Alderman, 1932), Wabar Craters (Philby, 1933), Campo del Cielo Craters (Nagera, 1926), Siberian Craters (Whipple, 1930), and now the Wolf Creek Crater in Australia have produced an overwhelming amount of evidence in favor of this meteoritic origin. The Wolf Creek Crater gives further support to the theory of Dietz (1946) and others who postulate a meteoritic origin for craters on the moon's surface.

From the available literature it appears that seven craters or groups of craters of meteoritic origin have been described (Spencer, 1933). Ashanti Crater, occupied by Lake Bosumtwi, Ashanti (Maclaren, 1931), and a group of craters in Estonia (Reinwaldt and Luha, 1928; and Kraus, Meyer, and Wegener, 1928) remain doubtful. Nininger (1948) also mentions that, in addition to the fall of meteors in Siberia in 1908, "now comes word that a similar, though smaller collision has occurred at a point some 200 miles north of Vladivostock."

Table 2, which gives the dimensions of craters of proved meteoritic origin, is of some interest. The variations in the ratios of width to depth may be explained by either erosion and sedimentation or by an initial accumulation of shattered rock or both. The figure given for the depth of the Wolf Creek Crater will be increased when the actual depth to bed rock is investigated.

AGE OF THE CRATER

Unfortunately, the youngest sediments in the area occupied by the crater are pre-Cambrian in age.

During the examination of the crater a few loose pieces of pisolitic ironstone or laterite were noticed among the fractured blocks forming the rim of the crater on the eastern side. As one descends the wall of the crater, the layer of laterite, from which the loose pieces were derived, may be seen *in situ* in the wall.

This is evidence that the meteor struck the ground and exploded after the laterite layer had been formed. Information which has been accumulating over the past few years favors late Miocene as the age of the laterite in northern Australia. It is, therefore, fairly certain that the Wolf Creek Crater was formed later than Miocene times.

TABLE 2

DIMENSIONS OF CRATERS OF KNOWN METEORITIC ORIGIN

	Width (Feet)	Depth (Feet)	Ratio of Width to Depth
Meteor Crater, U.S.A.	3,900	570	6.8
Wolf Creek Crater, Australia	2,800	170	16.5
Boxhole Crater, Australia	575	52	11.1
Texas Crater, U.S.A.	530	18	29.4
Henbury, Australia	360	60	6.0
Henbury, Australia	240	25	9.6
Henbury, Australia	30	3	10.0
Warbar Craters, Arabia	328	40	8.0
Campo del Cielo Crater Argentina	183	16	11.4
Siberia Crater, U.S.S.R.	164	13	12.5

The erosion of the crater is slight, and signs of erosion on the steep walls of the crater are not well marked. As far as could be ascertained, aboriginals in the area have no record of the meteor in their legends but are aware of the crater.

The evidence suggests, therefore, a Pleistocene or Recent age for the crater.

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QUARTZ CRYSTALS WITH CLAY AND FLUID INCLUSIONS[1]

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ABSTRACT

Quartz crystals with fluid and red-clay inclusions, characterized by a stout habit, double terminations, a more or less smoky or amethystine color, and high transparency, have been found in the upper Piedmont of North Carolina. Skeleton and phantom forms are common, and large groups of crystals show parallel orientation. They are the latest of several generations of quartz and have grown on older quartz which in most cases has determined their orientation. The quartz was probably deposited by ascending hydrothermal solutions, and the clay settled down on the growing crystals from levels nearer the surface. The rare and complex forms shown by the quartz suggest a changing physical environment, and the inclusions of red clay, the large volume of water present in some cavities, and the presence of associated carbonate minerals indicate an origin at moderate depths where temperature and pressure were low. Since crystals with large inclusions of water are shattered by freezing and since they are found close to the surface in areas that have suffered practically no erosion since the Pleistocene, it is concluded that soil in the upper Piedmont of the Carolinas was not subjected to deep freezing during glacial stages.

INTRODUCTION

Quartz crystals with inclusions of red clay are found at several places in a narrow belt extending in a northeast-southwest direction through Iredell, Alexander, Catawba, and Burke counties, North Carolina (fig. 1). Many of the crystals contain large cavities filled with water and movable bubbles. Such crystals do not occur on the surface, for they are easily ruptured, but they are found a few feet below. Though they have no intrinsic value, many have been discovered by mineral collectors and others in search of the valuable gem minerals and rare crystal forms of the district. However, only a small percentage of the crystals recovered is now preserved in museums and other collections since most of them have been shattered by freezing and a few by high temperatures.

Earliest references to the fluid-bearing quartz crystals of North Carolina are contained in papers of William E. Hidden (1881*a*, 1881*b*, 1881*c*, 1882, 1883*a*, 1883*b*, 1886*a*, 1886*b*, and 1887) and a brief note by John T. Humphreys (1881), both of whom were active in the search for rare and beautiful minerals. Many of the crystals were discovered in searching for emerald and for hiddenite, the green, gem variety of spodumene, found only in Alexander County, North Carolina. The rare and extremely complex forms developed on some of the quartz have been described by Hidden (1881*b*, p. 23, and 1886*a*, p. 208), Hidden and Washington (1887, p. 507), Miers (1893), p. 420, Pogue and Goldschmidt (1912), and Vom Rath (1884, 1885*a*, 1885*b*, 1885*c*, 1885*d*, 1886*a*, 1886*b*, and 1887); and figures are reproduced in Dana's *System of Mineralogy* (1892, p. 185).

In 1946 the writer visited the area in company with B. S. Colburn, W. A. Campbell, and W. B. Cormack, to all of whom he is indebted for assistance. Specimens were secured at that time, and others have been acquired since. The large group of specimens in the Colburn Mineral Collection now at the University of South Carolina has also been studied. Earl Ingerson kindly determined the temperature of disappearance of the vapor phase in the microscopic cavities of a crystal.

[1] Manuscript received June 14, 1949.

GENERAL GEOLOGY

The area investigated is located in the upper part of the Piedmont Province 40 miles southeast of the Blue Ridge Mountains. Outliers from the Blue Ridge, near the northwestern border of the area, rise 600–800 feet above the Piedmont peneplain which here has an elevation of 1,000–1,300 feet above sea-level. The Catawba and South Yadkin rivers and their major tributaries have cut their valleys 275–300 feet below the level of the peneplain, represented by the relatively flat divides.

The area is mantled by a thick blanket of residual material that, on divides just outside the area, reaches a thickness of over 100 feet. Where exposed, the bedrock is generally a biotite gneiss grading, in places, into mica schist. It is common-

FIG. 1.—North Carolina localities (*solid circles*) for quartz crystals with clay and fluid inclusions

ly well banded, with the strike in a general northeast-southwest direction.

Granite intrusions and numerous quartz veins and pegmatite dikes were observed. Most of the veins and dikes are small and lenticular in shape. Some are parallel and others transverse to the rock structure. A little commercial mica has been produced from some of the pegmatites, which also contain occasional crystals of beryl, spodumene, rutile, monazite, columbite-tantalite, and other rare minerals. Beryl, hiddenite, and rutile have been produced as gem stones, and a little quartz suitable for piezoelectric uses has been recovered. Rutile crystals with high luster are abundant, some showing the rare basal plane. They are commonly twinned and arranged in complex reticulated patterns.

The deep weathering occurred, for the most part, prior to the Pleistocene; and, on flat divides from which forests have not been cleared, almost no soil erosion has occurred since the close of Wisconsin time. Eargle (1940, p. 337) found, buried near valley heads notching the edges of the flat divides, organic soils in which Cain (1944) identified the pollen of trees that grow today where the mean annual temperature is at least 10° F. colder.

DISTRIBUTION AND DESCRIPTION

GENERAL STATEMENT

The individual areas in which quartz crystals with clay and fluid inclusions have been found are small and irregularly distributed along a 50-mile belt in a northeast-southwest direction. Other localities than those described are probably to be found, but they are of minor importance.

THE CAMPBELL FARM

In recent years the Campbell farm has been the principal source of clay- and water-bearing quartz crystals. It is located in Iredell County, 14 miles north-northwest of Statesville, on the gently rolling surface of the Piedmont peneplain, at an elevation of 1,000 feet, and 3 or 4 miles east of Spring Mountain. In 1930 B. S. Colburn recovered a considerable number of specimens from shallow pits and ditches on the Lambert farm and a few from the adjoining farm of W. A. Campbell. Mr. Campbell later acquired the Lambert farm and in recent years has done a little digging for the crystals, a few of which were used in making oscillator plates, while the rest went to mineral collectors. None of the excavations reached bedrock.

The country rock, where exposed in a stream bed, is biotite gneiss with strike of N. 80° E. It is cut by small pegmatite dikes and quartz veins. A piece of graphic pegmatite with much fractured quartz was found on the surface.

Residual sandy-clay soil mantles the country rock except where it has been removed by stream erosion. In a small patch of virgin forest the dark-gray topsoil (A-horizon) is 8 inches thick. In fields cleared and under cultivation for ninety years some of the topsoil is preserved although much of it has been removed by sheet erosion to expose the red B-horizon. The water-bearing quartz has been recovered from shallow pits and ditches on one side of a field where soil erosion since the forest was cleared is measured in inches and where the total erosion since the close of Wisconsin time could not be more than a foot or two.

Most vein quartz found on the surface is milky or gray to brown in color and much crushed so that the fragments are opaque. This quartz is older than the transparent quartz showing crystal faces.

Small quartz crystals with the steep rhombohedron $\{30\bar{3}1\}$ are found on the

property. They show faces of both the trigonal trapezohedron and trigonal bipyramid, and some are doubly terminated. Other minerals include a prism of yellow beryl 4 cm. in diameter, a short, doubly terminated crystal of black tourmaline, a rosette of radiating tourmaline in quartz, small prisms of rutile, and acicular inclusions of rutile in quartz.

Production of quartz with clay and water inclusions has been limited almost entirely to an area of about 1 acre. The crystals occur in the residual soil, singly or in clusters, most commonly attached to older, white vein quartz, and usually several specimens are found together. The best crystals, Mr. Campbell states, are found at depths of 3–8 feet. Nearer the surface they are chipped or broken, as though by freezing, and only a few thick-walled crystals contain small fluid-filled cavities.

The crystals, which are more or less equidimensional owing to the relatively small size of the prism faces, range up to 10 cm. or more in diameter (pl. 1, *A*). The steep rhombohedron $\{30\bar{3}1\}$ is present only as a narrow face beveling the edges between prism and normal rhombohedral faces. On a few crystals the edges between adjoining rhombohedral faces and between adjoining prism faces were replaced by narrow faces. Several crystals show the rare basal pinacoid $\{0001\}$ which, since it is seldom smooth, has been attributed by some mineralogists to corrosion. Trigonal trapezohedron and bipyramid faces are common, and many crystals are doubly terminated.

Some faces, the rhombohedral faces chiefly, are recessed or hollow with salient edges owing to relatively rapid growth at facial intersections and insufficient time for silica to reach the interior of faces by diffusion or circulation (pl. 1, *B*, *D*). A large fluid-filled cavity is formed through the bridging-over of such a depression by the growth of a continuous face, thus trapping some of the silica-bearing solution. This process is commonly repeated several times with the formation of chambered cavities, the cells of which may be entirely separated by the parallel partitions or may be interconnecting where partitions are incomplete. Cavities range up to 3 cm. in length and over 1 cm. in breadth, and the bubbles have a maximum diameter of 1.5 cm. One crystal contains two bubbles, one above the other, each a centimeter or more in diameter. Water seems to be the only liquid present.

The quartz crystals are colorless to dark brown or smoky, but even when the color is relatively dark, they are remarkably transparent. Near their bases and in central portions the crystals are mostly colorless, the smokiness being largely confined to the outer portions. The boundary between clear and smoky quartz may be sharply defined or gradational. One crystal shows two thin layers of smoky quartz parallel

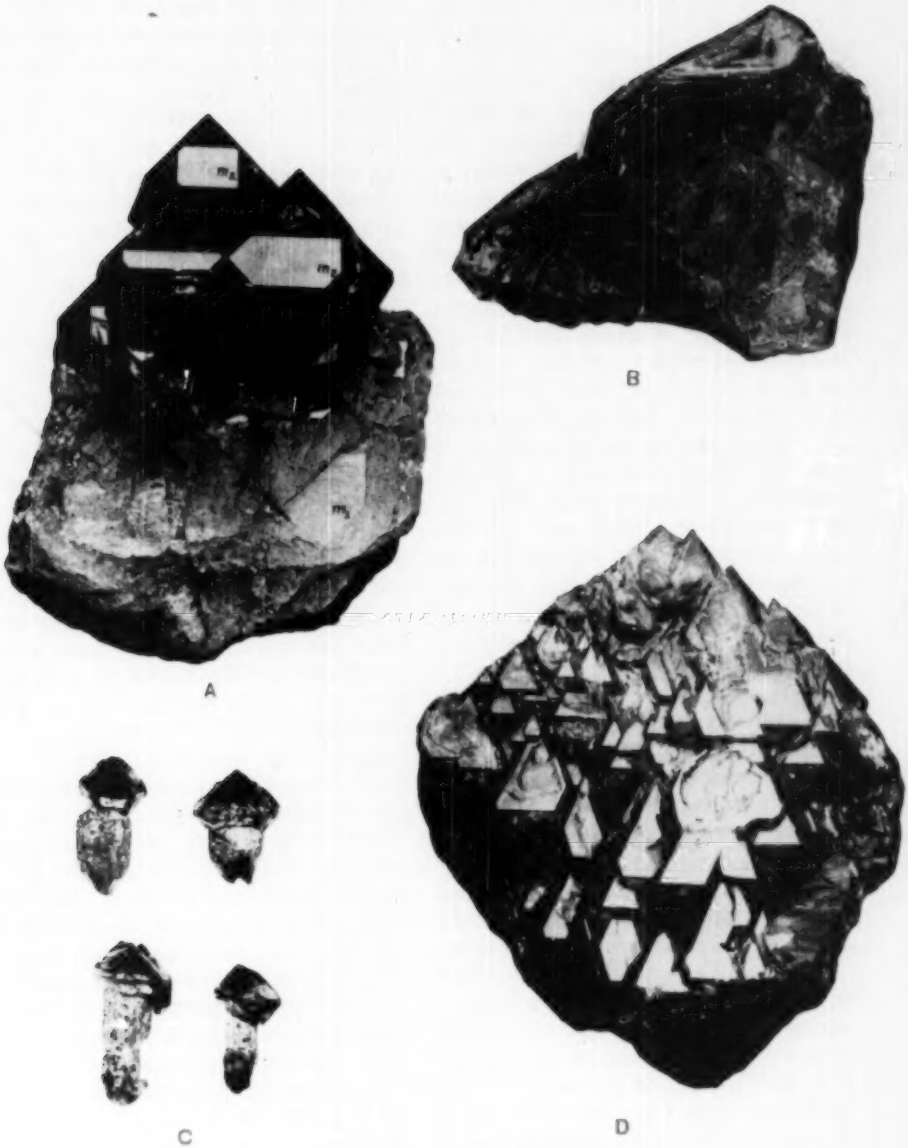
PLATE 1

A, Clear smoky quartz on older milky quartz with parallel orientation. The prism faces of the old quartz (m_1) and of the new quartz (m_2) are parallel. The surface of the specimen is 7½ × 10 ½cm.

B, Crystal of clear quartz with hollow rhombohedral face and numerous inclusions of red clay in thin parallel layers. The surface shown is 7½ × 7½ cm.

C, Amethyst capping slender forms of milky quartz. Horizontal diameter of the amethyst crystals is 0.9 cm.

D, Rhombohedral faces of clear quartz (white) on a single crystal of milky quartz, all having parallel orientation. Some of the large faces are recessed with salient edges. The surface of the specimen is 20 × 24 cm.



Quartz crystals

to rhombohedral faces and separated from one another and from the surface by colorless quartz. Some small, doubly terminated crystals are smoky throughout. The presence of monazite in pegmatites at the Hiddenite Mine and at other localities in the area is in line with the hypothesis that smokiness in quartz is due to radioactivity, but the zonal arrangement in some crystals and the limitation of the color to the youngest quartz suggests that the coloration was induced only at certain stages during crystal growth.

The surprising beauty of the specimens is due to the paper-thin layers of red clay (pl. 1, *B*) enclosed in highly transparent quartz which has a brilliant luster on crystal faces. As a rule the layers show the deep-red color characteristic of clay soils in the southern Atlantic states, but in one crystal the clay is pink and in another it is almost white. The clay layers are sharply defined instead of being more or less diffused as in typical phantom crystals, and they are closely spaced, some crystals having more than five per centimeter. The layers are parallel to both prism and rhombohedral faces, more commonly to the latter. Their absence on one side of some crystals suggests that the clay particles settled downward through the depositing solutions and came to rest on exposed upper surfaces, but this hypothesis could not be proved since the crystals have been displaced during the weathering of the enclosing rock. Intermittent deposition of clay during crystal growth may be due to repeated crustal movements, such as resulted in the formation and reopening of fissures, and to the accompanying earthquakes. The crystals with clay and fluid inclusions are the youngest of several generations of quartz. They contain tourmaline but only at their bases, and no tourmaline or other mineral has been implanted on them during or subsequent to their growth.

The older vein quartz appears to be arranged in a haphazard manner with no uniformity in crystal orientation, but the youngest quartz commonly forms groups of crystals (pl. 1, *A*, *D*) most of which are similar in size and all with corresponding faces parallel. Individual groups may be 45 cm. or more in diameter, and some specimens consist of two or more groups, each with its own orientation. Each group is implanted on a single crystal of the older quartz which has determined the orientation of the later growth (pl. 1, *A*). All stages in the formation of the groups may be observed. Growth of new crystals begins at numerous centers of nucleation on a fractured surface of the older parent-crystal. The fracture surface, though irregular in detail, is in most cases roughly parallel to a rhombohedral face, thus conforming to the poor cleavage possessed by some quartz. Each group of crystals with parallel orientation is, therefore, in fact a single crystal exhibiting two periods of growth, but in describing such specimens it is convenient to consider them as groups of individuals. Incipient growth of crystal faces on the back of some specimens faced with a group of large crystal faces suggests that some deposition of silica may have occurred since the mass was detached from the wall, but this is doubtful.

Adjacent parallel faces in growing occasionally coalesce to form a single continuous face, but the general failure to repair a broken crystal by building up a single face instead of a group of parallel faces is probably due to the same cause as that which formed the hollow faces of skeleton crystals—the relatively rapid growth on the more accessible faces with

insufficient time for silica to reach the less accessible surfaces. A few individual crystals of the younger quartz appear to be independent of the older quartz on which they are implanted, for parallel orientation is absent.

THE SHOEMAKER FARM

A few quartz crystals with clay and fluid inclusions have been found on the farm of W. B. Shoemaker, ½ mile west of the Campbell farm. They seem to be similar in every way to those obtained at the latter place.

THE HIDDENITE MINE

The best-known and most thoroughly explored mineral locality in the district is the Hiddenite Mine in Alexander County, 1 mile northwest of the railroad station and post office of Hiddenite and 15 miles northwest of Statesville. Mineral relationships here were studied by Davidson (1927, pp. 305–307) and by Palache, Davidson, and Goranson (1930, pp. 280–302) while the mine was being worked by B. S. and W. B. Colburn.

The mine is on the flat divide between the South Yadkin and Catawba rivers at an elevation of about 1,150 feet. The mantle of residual soil is 10–15 feet thick in the Colburn pit, but Hidden (1883*b*, p. 501) found it to be 26 feet in one of his excavations. Transition from soil to fresh rock is quite abrupt.

The country rock, a much contorted quartz-biotite gneiss, contains plagioclase, garnet, zircon, apatite, and small amounts of a few other minerals. Palache, Davidson, and Goranson (1930, p. 281) point out that the relatively high percentages of quartz and of rounded zircon grains indicate that the gneiss was initially an argillaceous sandstone. They describe a complex genetic history for the deposits (1930, p. 301), including several periods of metamorphism, repeated folding and fracturing with the injection of migmatites and pegmatites, and, finally, the formation of vug and cavity minerals which are listed in sequence as "quartz, hiddenite and beryl, mica, albite, siderite and flat rhomb calcite, quartz, monazite and rutile, adularia, pyrite, calcite, followed by corrosion of practically all of the minerals and some oxidation of pyrite to limonite."

The mineral "pockets" or cavities vary greatly in size and in mineral content. Those found in the Colburn pit were small, but Hidden (1882, p. 132) describes one with depth of 16 feet, width of 3 feet, and length of 7 feet and another (1886*b*, p. 483) that extended 20 feet in a nearly vertical direction. Hidden's list of minerals present in different cavities (1883*b*, p. 501) includes quartz, rutile, mica, monazite, dolomite, calcite, apatite, rutile, pyrite, and beryl.

Quartz crystals with large fluid inclusions were not encountered in the Colburn pit, but Hidden found several pockets with many crystals. He describes one pocket (1882, pp. 131–136) as follows: Quartz fragments and mica flakes on the surface indicated the presence of a vein that cut across the rock structure. Solid quartz, encountered at a depth of 1 foot, widened to 3 feet at a depth of 6 feet. The miners then passed through red clay with small quartz crystals and at a depth of 9 feet broke into a cavity, 3 feet wide, 7 feet long, and 3 feet deep, coated with red clay in stalactitic forms. The quartz, which had once lined the vug, had fallen to the bottom, and it was only here that crystals were found *in situ*. Crystals that had been directly attached to the walls were semitransparent and without much development of prismatic faces, while implanted upon them were well-formed, transparent crystals varying from citrine-

yellow to dark chocolate-brown in color. These youngest crystals contained the fluid inclusions. They were large, none less than 2 inches in diameter, many weighing over 3 pounds. One dark-brown doubly terminated crystal weighed nearly 25 pounds. The largest fluid-filled cavity was nearly $2\frac{1}{2}$ inches by $\frac{1}{4}$ inch, cavities 1 inch long were common, whereas those of $\frac{1}{4}$-inch were numberless. Many crystals had chambered cavities with numerous thin, parallel partitions. The pocket yielded nearly half a ton of crystals, over 400 pounds of them being choice specimens. Clay inclusions have not been reported previously in quartz from the Hiddenite Mine; but a diligent search disclosed a number of flat transparent flakes broken from cavernous crystals, mostly parallel to a rhombohedral face, and a few of these contained red-clay inclusions.

Quartz closely associated with hiddenite has a different habit from that described above. The crystals, called "hiddenite quartz" by the miners (Hidden, 1886*a*, pp. 204–205), are small slender prisms capped by the acute rhombohedron $\{30\bar{3}1\}$. Specimens in the Colburn collection closely resemble similar crystals from the Campbell farm, though no hiddenite has been discovered there. A few of the crystals are smoky in color, and some are not very transparent.

Slender, colorless quartz crystals capped by a later parallel growth of pale amethystine quartz having a stout habit were observed in a few narrow crevices by Palache, Davidson, and Goranson (1930, p. 287). Hidden (1881*b*, p. 25) previously reported the presence of this "scepter-quartz" which is also found elsewhere in the area. Specimens in the Colburn collection have the habit and other characteristics of the larger fluid-bearing crystals.

THE HEFNER FARM

Mr. Oscar O. Hefner's farm, 5 miles north of Conover, has yielded rare and interesting types of quartz. John T. Humphreys (1881, pp. 75–78) first reported unusual quartz crystals from this area. A few miles east of Hickory in a deposit of "drift gravel" extending in a northeast-southwest direction he found, at a depth of 2 feet, a pocket of water-bearing, smoky quartz crystals, some "clay-tessellated" and some with the basal pinacoid. Amethyst and quartz crystals enclosing mica, pyrite, rutile, and red clay were obtained. Later he discovered fifteen new localities for water-bearing quartz crystals, obtaining as many as 550 specimens, nearly 70 with basal planes.

The Colburn collection contains a representative set of specimens from the Hefner farm found by W. B. Colburn and Mr. Hefner. The crystals with clay inclusions are similar to those from the Campbell farm. One shows the trigonal pyramid and trapezohedron faces and a rough basal pinacoid. The rhombohedron $\{30\bar{3}1\}$ bevels the edges between prism and unit rhombohedral faces. Large fluid inclusions are present in some crystals.

Amethyst containing inclusions of minute acicular rutile is found capping slender prisms of colorless quartz (pl. 1, *C*). It shows the parallel growth and stout habit characteristic of similar specimens from Alexander County and also from Lincoln County (Kunz, 1907, p. 32 and pls. V, *D* and *E;* VI, *B;* and VII, *B*). Some Lincoln County amethyst shows rare faces, and some encloses water. A variety of translucent quartz not reported elsewhere in the district has a green color due to inclusions of fine chlorite. Many crystals are small, splendent, and much flattened parallel to a prism face. Some crystals, more normal in form, are

partly transparent with the chlorite forming multiple phantoms (fig. 2), the distribution of included material being such as to suggest that it had settled through the silica-depositing solution under the influence of gravity and had come to rest on upper surfaces of growing crystals. Other minerals are beryl (aquamarine), black tourmaline, and red rutile with high luster.

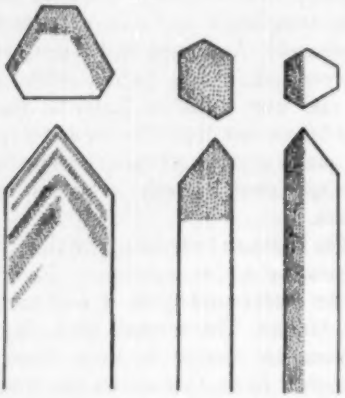


FIG. 2.—Phantoms due to chlorite inclusions in quartz crystals.

BURKE COUNTY QUARTZ

Humphreys (1881, p. 77) reported finding liquid-bearing quartz crystals and crystals showing the basal plane at two localities in Burke County. Kunz (1907, pl. VIII, *B*) shows a photograph of a group of crystals enclosing clay and water. The crystals have parallel orientation and skeleton forms similar to those found on the Campbell farm.

EFFECTS OF HEATING CRYSTALS WITH FLUID INCLUSIONS

The large bubbles in quartz from the Hiddenite Mine seem to behave differently from those in quartz from other localities in the belt. Hidden (1882, p. 136) states that if a specimen was slightly heated (the heat of the hand being sufficient), the bubbles disappeared entirely. On cooling, a critical temperature was reached, when the cavities were filled with numberless minute bubbles, which united to form a single bubble again.

Water-bearing crystals from the Campbell and Hefner farms were gently warmed by the writer, but the bubbles did not disappear. Four crystals from the Campbell farm were suspended in water and the temperature slowly raised to 90° C. through a period of 7 hours. A mechanical stirrer kept the temperature uniform throughout the container. One crystal was ruptured at 80° C., but the others were not affected at 90° C. Mr. Campbell states that some specimens were destroyed when left in the sun on a hot day. The temperature at which crystals rupture depends on several factors, such as size and shape of the cavities, thickness of the enclosing walls, and the presence of weakening flaws.

The quartz crystal, broken in the experiment described above, was later used by Earl Ingerson in determining the temperature at which the vapor phase disappeared in microscopic cavities. A slice parallel to the *C*-axis was cut out of the middle of the crystal, and then five small plates were cut in approximately the positions indicated in figure 3. The cavities in the various plates were completely filled with liquid at temperatures ranging from 125° C. to 160° C. (table 1). These temperatures have been corrected for position and calibration of the thermometer but not for pressure due to depth below the surface at the time the crystal was formed.[2]

[2] Letter from Earl Ingerson dated February 17, 1948.

Similar tests made by Ingerson[3] on specimens of quartz collected by J. B. Mertie from a mica mine 8 miles northwest of Shelby, North Carolina, gave temperature ranges as follows: five specimens of "pocket" quartz, 158°–208° C.; five specimens of vein quartz, 160°–205° C.; and four specimens of pegmatite quartz, 160°–182° C.

The temperature determinations in table 1 show a considerable range for a single crystal and may indicate changes in temperature during crystal growth. In general, they are lower than those obtained on the other North Carolina quartz, and they tend to support the conclusion in Taber's abstract (1946, p. 1234) that the quartz crystals with clay and large fluid inclusions were formed at relatively low temperatures. The crystals found at the Hiddenite Mine may have been formed at somewhat lower temperatures.

TABLE 1

TEMPERATURES REQUIRED FOR DISAPPEARANCE OF VAPOR PHASE IN CRYSTAL CAVITIES

Plate No.	Degrees C.
1	152
2	150, 159
3	155, 157
4	125, 125, 128, 152
5	158, 160, 160

EFFECTS OF FREEZING CRYSTALS WITH LARGE FLUID INCLUSIONS

Susceptibility of crystals with large fluid inclusions to damage by freezing is well illustrated by the experience of Hidden (1882, pp. 134–135). He discovered the pocket containing so many water-bearing crystals October 24, 1881, and in November left them nicely arranged at the mine except for a few small ones which were carried to his log cabin. During the night the temperature unexpectedly dropped below freezing. He writes:

> About midnight I was awakened by several sharp reports, like the explosion of gun caps. . . . In the morning . . . on the table where the crystals had been placed . . . there remained now only some few sharp fragments of quartz. Pieces of the crystals, large and small, were found even fifteen feet away. . . . I returned to the mine . . . to find not one of them, even the smallest, left intact. . . . Those with few cavities had burst, scattering large fragments, widely separated; while those containing minute cavities lay as a heap of small fragments frozen together *in a coherent mass*. This . . . shows conclusively the abundance of the fluid included. . . . I had these masses and larger fragments carried out and placed in the sunlight, . . . as soon as the rays of the sun touched them . . . an ebullition commenced. . . . I noticed in some of these masses a very distinct odor of sulphuretted hydrogen, which was quite fugitive in some of the pieces, while constant in others. This ebullition was continued for over an hour, growing less as thawing progressed.

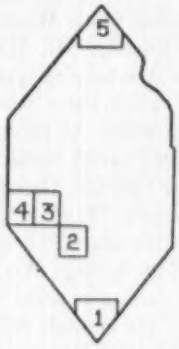


FIG. 3.—Diagram showing location of plates tested by Ingerson.

The ebullition was probably due chiefly to escape of carbon dioxide imprisoned by the rapid crystallization of water. Freezing was rapid because of the sudden expansion in volume of the fluids

[3] Written communication dated December 29, 1947.

immediately following rupture of the crystal.

The average minimum temperatures at Statesville, North Carolina, for October and November are 47°.2 and 36°.5 F., respectively (Martin, 1933, p. 17), and the temperature in early November in unheated buildings could not have been more than a very few degrees below freezing.

Quartz crystals from the Campbell farm and the other localities in the area have been ruptured by freezing. The North Carolina State Museum, according to the director, Mr. Harry Davis,[4] lost all its water-bearing quartz crystals by freezing when they were sent to a Chicago exposition. An amethyst crystal with fluid-filled cavity obtained by C. E. Hunter[5] near Clayton, Georgia, was ruptured by freezing. Hugh D. Miser[6] states that the water-bearing quartz crystals found near Hot Springs, Arkansas, occur close to the surface in areas of low relief, and many of the crystals recovered have been ruined by freezing.

DISCUSSION AND CONCLUSIONS

A large variety of quartz crystals is found in the North Carolina Piedmont. They differ from one another in habit, color, transparency, mineral association, and relative age. The crystals containing clay and large fluid inclusions belong to the youngest generation of quartz. They are implanted on older quartz, which has commonly controlled their orientation. Some of them contain inclusions of older minerals, especially near their contacts, but no minerals were found implanted on these crystals. They have a stout habit and usually show double terminations, high transparency, and a more or less smoky or amethystine color.

The groups of crystals with parallel orientation and the skeleton forms suggest relatively rapid growth with insufficient time for the completion of large faces. Rapid crystallization under changing conditions may also help explain the rare and complex forms. Etching of crystal faces, multiple phantoms, "scepter-quartz," and other crystals showing two or more generations with common orientation, all furnish evidence of changing conditions during crystal growth.

The presence in the hiddenite vugs of the relatively high-temperature minerals, albite, adularia, beryl, and muscovite, together with the low-temperature carbonates, calcite, ankerite, and siderite, suggests that mineral deposition took place over a considerable range in temperature.

The transparency of the younger quartz is due, initially, to crystallization in open spaces and, therefore, to the absence of stresses due to mutual interference of crystals growing in contact with one another. Moreover, these crystals have not been crushed and distorted by the crustal movements that have affected most of the older quartz. Crystals containing inclusions with coefficients of expansion different from their host are subjected by change in temperature to stresses tending to cause fractures and consequent milkiness. Also, quartz has different coefficients of expansion in different crystallographic directions. The transparency of these crystals, therefore, indicates that they were formed subsequent to the crustal movements that have damaged most of the earlier generations of quartz and that in reaching the

[4] Oral communication, November 16, 1946.

[5] Oral communication, November 16, 1946.

[6] Letters dated January 14 and February 19, 1947.

surface they have undergone only moderate changes in temperature and pressure.

The red clay present in many of the quartz crystals probably settled down from the belt of weathering, and, since the veins are not very persistent in strike or depth, this suggests deposition at relatively shallow depths. Most of the crystals have been found in the deep residual soil of the area, but the linear distribution of quartz fragments on the surface, which has been used as an indicator in prospecting for the crystals, shows that they have come from vugs in small veins broken up as a result of weathering of the enclosing country rock.

The Piedmont of the southern Atlantic states contains numerous granite intrusions and closely associated mineral deposits which show all gradations from granite through pegmatites to quartz veins. The quartz crystals with red-clay and water inclusions were probably deposited at relatively low temperature and pressure by hydrothermal solutions derived from deep-seated granitic magmas, and these crystals represent the last phase in the mineralization of the district. They developed under temperatures and pressures that were lower than those prevailing when most of the quartz was deposited. Some solution channels became choked by minerals deposited during earlier stages and were not reopened. Others were reopened from time to time by crustal movements which also opened up new channels. This has resulted in great diversity in mineral composition of the dikes and veins even within very limited areas. Aragonite and limonite in some vugs are probably due to descending meteoric water.

Vulnerability of water-bearing crystals to freezing makes possible their use as an aid in determining minimum temperatures to which certain areas have been subjected. Some geologists have attributed the burial of organic soils and other Piedmont phenomena to mass movements during a periglacial climate, often described as a climate cold enough for perennially frozen ground. Since the water-bearing crystals were obtained by Hidden, Humphreys, Colburn, and Campbell at depths as shallow as 2 feet and in localities that have suffered almost no erosion since Wisconsin time, the soil could not have been perennially frozen. The cold-climate trees identified by Cain (1944, pp. 15–21) now grow in New England where the average depth of frost penetration ranges from 2 to 6 feet (Kohler, 1941, p. 747). The ice-age climate of the Carolina Piedmont was similar to that of New England today.

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STEREOSCOPIC PROJECTION FOR DEMONSTRATION IN GEOLOGY, GEOMORPHOLOGY, AND OTHER NATURAL SCIENCES[1]

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ABSTRACT

Pictures in three dimensions have great advantages over flat ones for teaching geology and other sciences. Not only do they give a very much clearer and more detailed view, but the stereoscopic effect is so fascinating that a photograph viewed in this form imprints itself more deeply on the mind. The technique is simple.

The great value for map construction of stereoscopic photographs, whether taken from the ground or from the air, is generally acknowledged. Most geologists and other natural scientists fail, however, to appreciate the conspicuous advantage of three-dimensional pictures over two-dimensional ones for documentation and demonstration in a wide range of subjects. When refreshing one's memory by photographs of an exposure examined in the field, it is surprising to find how vividly many details stand out in stereoscopic prints which escape unnoticed in flat ones. Needless to say, in demonstration to others who have not visited the locality the third dimension is of even greater value. But the stereoscopic effect gives unique assistance when teaching the earth sciences to students for two reasons. (1) Those who are as yet unfamiliar with field geology have greater difficulty than old field hands in interpreting flat pictures as solid subjects because they are not yet accustomed to think in space and because they are viewing matters which are quite new to them. The development of this faculty of thinking in three dimensions is one of the main purposes of field excursions. By demonstration with stereoscopic pictures the student is already initiated into this form of mental gymnastics while acquiring at the same time a better grasp of the feature under discussion. (2) The stereoscopic effect in photography is so striking and so fascinating that a picture viewed in this form imprints itself much more firmly on the mind than does a normal flat one. Stereoscopic demonstration comes appreciably nearer to the experience of having actually inspected the exposure in the field. This advantage is particularly marked when teaching students in a university far removed from mountainous areas where the lack of sufficient training in the field makes itself adversely felt. Although stereoscopic demonstration can never replace excursions, it goes a considerable way in giving training that can otherwise be obtained only by expensive and time-consuming travel. The enthusiasm of a class over a fine stereoscopic picture stimulates their interest; and the pupils' interest in the subject is, after all, the first condition for successful teaching.

One of the reasons that stereoscopic effect in a photograph is so striking is that both near-by and far-off objects can be viewed without altering the focus of the eye and by merely shifting the eye axes. The small optical aperture of a photographic lens affords greater depth of focus to a print than the eye can give

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even in strong lighting. When one is looking at a scene in nature, the focus has to be altered along with the shifting of the eye axes. Hence the impression of depth in the photographs is attained with less effort and more instantaneously than in nature.

What this effort is can be easily tested by closing one eye and holding an object before a distant background. It will be found that focusing first on one and then on the other entails an appreciable effort and lapse of time. The eye can run over a stereoscopic photograph of a similar subject with perfect ease and with uninterrupted vision. To this ease in appreciating the third dimension must be attributed some of the fascination of stereoscopic pictures. Naturally the focusing action is a help for judging distance in nature, and hence a distance can be more accurately estimated than it can from a stereoscopic print. Nevertheless, this does not offset the curiously impressive "feeling" of space experienced when using a stereoviewer.

To the advantages already mentioned can be added one of the utmost importance in studying large objects. While stereoscopic vision is limited to a depth of about 50–100 meters because of the small distance between the eyes, it is a simple matter to take pictures with a larger base. This principle is used for obtaining aerial stereoscopic pairs, where the distance covered by the plane between the taking of two exposures represents the enlarged eye distance. Likewise with ground photographs for stereophotogrammetric purposes a large base is used.

The latter technique requires an accurately known base line and minute precision in sighting (alignment of the cameras). It will be found, however, that by merely aiming the camera twice at the same object in the far distance while side-stepping a few meters between the exposures (preferably with no close foreground or only a smooth one) a remarkably fine depth effect is readily obtained. To estimate the sideways shift required, it is sufficient to divide the distance to be covered by a few hundred. The writer's experience is that a distant view requires side-stepping 3–6 meters, but no fast rule can be given because some subjects are relatively flat while others have a great range in depths, the former needing a larger base when viewed from the same general distance away.

If the aiming has been faulty, especially if the horizons are not parallel, viewing may cause some trouble. It is a small matter to grind the edges of one of the slides until perfect adjustment is obtained.

Conversely, it may be wished to obtain a three-dimensional picture of a small object. In this case normal use of a stereoscopic camera coupled with an extra lens for reduction of focal length is impracticable. The images formed by the lenses of an object held at a distance of a few centimeters from the camera fall outside the frames (fig. 1, *B*). This difficulty can be overcome by taking separate exposures, while holding the object in front of each lens in turn. But a slight rotation around an axis parallel to the short side of the camera back (normally the vertical) should be given to the object while moving the lighting to correspond (fig. 3). Alternately, the direction of the axis of the camera can be shifted, thus eliminating the necessity of altering the lighting (fig. 2). The amount of rotation determines the degree of stereoscopic effect and can be regulated so as to give a natural or an exaggerated result.

Naturally it is not necessary to use a stereocamera in either of the cases in

which two successive exposures are made. A microphotograph can thus also be made three-dimensional. But sharp focusing over the entire field will be difficult to obtain with greater enlargements.

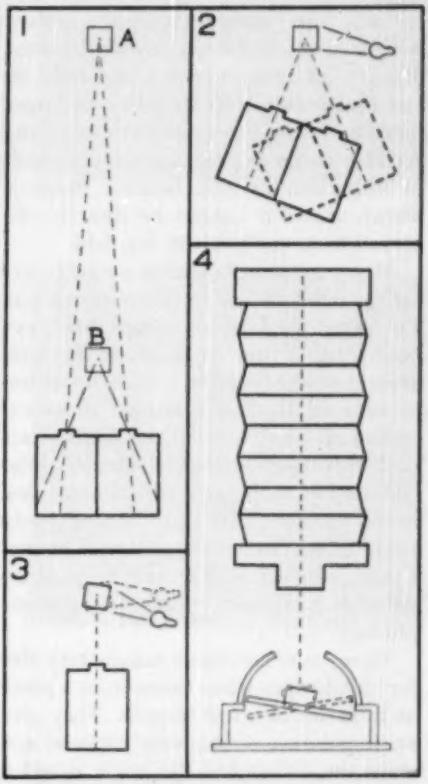
A useful setup is to put the object on a universal stage placed over a piece of black paper, omitting the half-spheres when using light from above (fig. 4). The amount of tilt can then be regulated accurately. A tilt of the order of 2–3 degrees is satisfactory; but if one wishes to exaggerate the depth, a larger angle can be used. For a subject with small relief this may be advisable. But in the latter case the lighting should be shifted accordingly, which is hardly necessary with a tilt of a few degrees only. A small diaphragm is necessary to insure sufficient depth of focus.

Using this arrangement, where the tilting is around an axis at the back of the picture, the object will appear to stand out in front of the projection screen. The effect is most realistic. But a landscape or other out-of-doors subject should be shown as if viewed through a window in the darkened lecture hall and should therefore appear behind the screen. This is taken care of automatically by a normal stereocamera.

Sand grains, foraminiferal tests, crystals, and similar objects stand out beautifully in the stereoprints and show the shapes, frosting, and internal luster, or inclusions of clear minerals, etc.

Some further examples of subjects particularly suitable for stereoscopic demonstration may be given, but it is the writer's experience that with almost any subject there is some gain.

Any assortment of objects lying at varying distances from the camera shows up in a normal photograph in wrong size proportion. Thus, a shingle ridge photographed from the shore in front appears to grade upward into smaller-sized pebbles because of the greater distance from the camera at the top than at the bottom. A stereopicture counteracts this optical illusion. The size of any unfamiliar subject cannot be judged without a measuring rule. An object for comparison is often used (hammer, matchbox, human figure), but such an object cannot be placed on an inaccessible subject (unscalable cliff, canyon wall, volcanic crater, beach swept by waves, opposite side of a stream, etc.). In addition, a stereopicture enhances the accuracy and over-all effectiveness of an object of comparison.



FIGS. 1–4.—Camera arrangements for stereoscopic photography.

Tectonic structures can be studied to particular advantage with stereophotographs because hardly any exposure is flat and can be viewed from a spot opposite its center. The true solid shape of a pitching fold, a fold viewed under an angle to its strike, warped surfaces, and tectonic forms showing up in the surface relief of a landscape are among the most difficult subjects to render faithfully on two-dimensional pictures. Here a larger base can be used to great advantage, the result sometimes even outstripping that of inspection *in situ*, because shape is shown where it cannot be directly observed from one point in the field.

Many geomorphological subjects are on a grand scale and in this respect are in the same need of an exaggerated eye base. Still, a tree or fence in the foreground will be found to conjure up an impression of depth in a normal stereo exposure far away beyond the limits of actual three-dimensional rendering. Glacial-erosion, river terraces, dunes, gorges, runoff patterns, etc., are among likely subjects for stereoscopy. Aerial stereoscopic pairs are well known to be of invaluable assistance in studying geomorphology.

Stereopairs are highly satisfactory also for cloudscapes when taken from a plane at intervals of a few seconds. They give an impression of immense expanse and show the shapes and the levels at which the clouds are floating. Another field is found in botany, where the third dimension renders the demonstration of a plant association much more efficient because size is shown and separate plants can be picked out with greater ease.

In crystallography and mineralogy one is able to show small crystals and structure models in natural shapes and color to a large audience.

Anatomical preparations or operation details can be demonstrated to large groups of medical or zoölogical students. Chemical or physical experimental setups are likewise excellent subjects for stereoscopic projection. It is even possible to show the sphericity of the moon by combining pictures taken at different stages of the nutational movements. The writer has seen a stereoscopic pair which was made in this manner a century ago.

In short, for all natural sciences three-dimensional projection can be used to advantage, although geology is probably the subject in which the greatest gain can be realized.

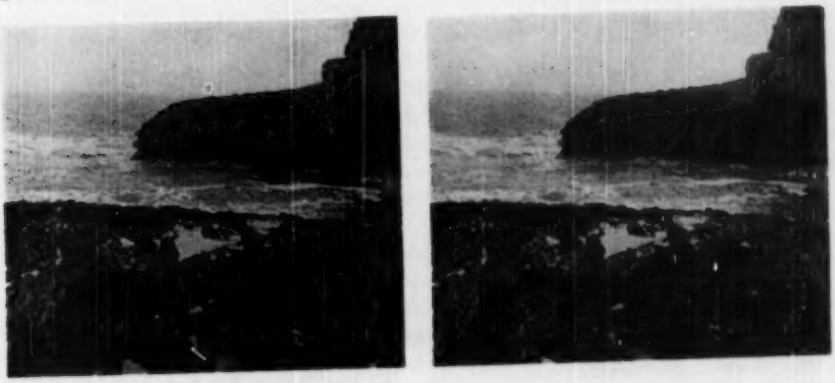
One of the reasons that stereophotography has been neglected by almost all geologists is the cumbersome apparatus formerly required. Now that excellent small stereocameras are being produced, by Richard of Paris among others, this objection no longer exists. His camera uses 35-mm. film and is handled exactly as are single-frame cameras (automatic focusing by view finder, rewinding coupled with film transport), the weight being only slightly greater. Single frames can be made by the simple process of setting a knob in a different position. But, as pointed out above, single-exposure

PLATE 1

A, Marine attack on horizontal Carboniferous limestone, Pembrokeshire, Wales. Mainly solution, giving sharp-edged forms in foreground; partly mechanical, giving rounded shapes toward surge channel along fault line.

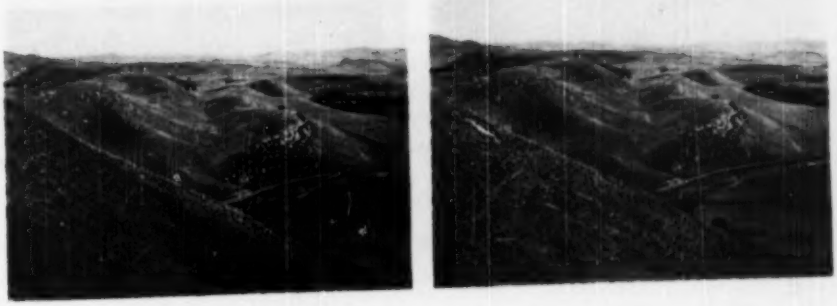
B, Boulder beach ridge, mainly sandstones resting on Carboniferous shale, average diameter 30 cm. In single print false appearance of grading upward into smaller blocks. Pembrokeshire, Wales.

C, Syncline extending into a basin in middle distance, formed of Weka Pass limestone (Oligocene), Canterbury, New Zealand. Stereobase about 4 m.



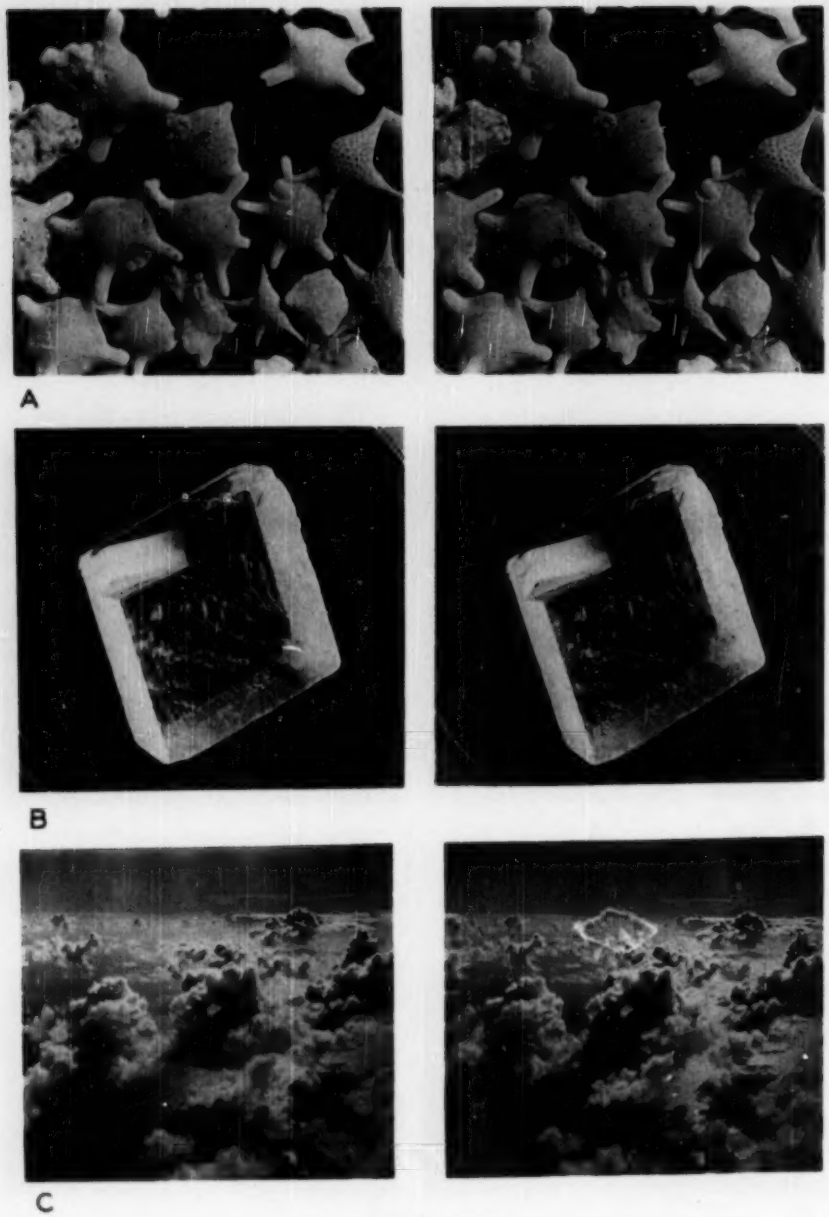
A

B



C

Stereoscopic photographs



Stereoscopic photographs

cameras can be used on any stationary subject. A simple gadget may be placed on a tripod to insure the correct amount of shifting and parallelism of the optical axes.

A further noteworthy advantage of the small frames is that the depth of focus is greater with the short focal length of the lenses than with larger-sized cameras. In stereoscopic photography this is of even more importance than in flat pictures. In the latter case the blurring of objects out of focus helps to render the distance and may therefore sometimes be taken into the bargain, while in stereoscopy this blemish can and should be avoided to the utmost.

Another and very serious obstacle has been the difficulty in showing stereoscopic pictures to an audience of more than one. Stereoscopic projection by means of a red and a green image viewed through spectacles with the same colors is unsatisfactory for photographs and has never been used by geologists as far as the writer is aware. He would like to call to the attention of teachers in science that a highly satisfactory method is now available for showing three-dimensional photographs, either black and white or colored, by means of polarized light.

Originally proposed more than half a century ago, this system did not become practical until polarizing filters (bernotar, polaroid) were produced. It is so simple that one need not buy an outfit but can make it with very little trouble. Two identical projectors are placed side by side at a sufficient distance apart to allow easy manipulation of the slide carriers. They must be adjustable by means of screws so that the images are brought into superposition on the screen. Even if the prints are made with great care, when each new pair is thrown on the screen, an adjustment of a few inches both horizontal and vertical is required.

The light is polarized by a disk of polaroid inserted between the slide and the projection lens. The polarization planes should both slant at 45° in opposite directions, not vertical and horizontal; otherwise the two pictures do not show with equal brightness. Each member of the audience views the picture through spectacles also fitted with polaroid. The polarization plane of the lantern showing the left-hand picture must be the same as that of the left-hand eyepiece of the spectacles. The screen must be of the aluminum type, because dull white screens depolarize the reflected light. This system has the further great advantage that colored prints can also be shown, although the polaroid causes some loss of brilliance. The use of lamps of more than normal strength combined with fans for cooling is advisable.

The system described can, of course, be used for various sizes of slides. But the 5-by-5-cm. (2-by-2-inch) size for Leica slides is the most satisfactory. In the first place, very bright images are then obtained. In the second place, color film is less expensive in this small size. In the third place, both a stereocamera in this size and the slides (double in number as compared to ordinary projection) are

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PLATE 2

A, Coarse sand formed of Foraminifera and coral debris, Sibutu, Philippines. Tilted 5° to give stereo effect. ×8.

B, Sodium nitrate, showing artificial glide twinning and inclusions. Tilted 3° to give stereo effect. ×1.6.

C, Cumulus clouds from an altitude of about 3,000 m., tropical Pacific. Stereobase about 200 m.

light. Finally, as pointed out above, the short focal length insures great depth of focus.

It might be thought that stereoscopic pictures take much more time to manipulate than single ones. As long as right and left pictures are clearly marked, a trained assistant can easily show three to four a minute. Thus practically no time is lost. Besides, since there is more to see in each picture, there should be ample time available for putting in the new slides.

It must be admitted that the best view is obtained only from the seats along the central line of a lecture hall. Toward the sides the brightness of a picture on an aluminum screen falls off quickly, and some distortion of three-dimensional shapes occurs. Hence in a normal lecture hall several seats on the wings of the front rows give a poor view of the pictures. Normally this should not be serious except for some 10 to 15 per cent of the seating capacity. The greater the distance of the observer from the screen the greater the apparent depth of the picture will be. The correct amount of stereoscopic effect is obtained at a distance from the screen dependent on the size of the image. Pictures 1½ by 2 meters are quite satisfactory for all individuals in an audience of about fifty.

The writer's attention has since been drawn to some earlier papers on the subject of stereoprojection (Fisher, 1942*a*, *b*).

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STUDIES FOR STUDENTS

THE DOWN-STRUCTURE METHOD OF VIEWING GEOLOGIC MAPS[1]

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ABSTRACT

Most contact lines on geologic maps are surface traces of inclined planes. If the map is viewed down the slope of these planes, it becomes, in effect, a section, and the map patterns are seen as structures. The "down-structure" method of looking *into* maps rather than *at* them can be introduced into the most elementary exercise in geologic map interpretation; it helps the student to grasp quickly the structural significance of patterns on maps made by others and increases his sensitivity in laying down lines on his own maps in the field. Used with proper caution and an understanding of its limitations, the method is applicable to a wide range of map patterns, from those of simple monoclinal structures to those of recumbent folds.

INTRODUCTION

1. Professor X is discussing Alpine structures with a small group of graduate students. After he has given a routine explanation of the areal geology of a nappe complex depicted on a wall map, the map is returned to its cabinet, and a sheet of sections is hung before the class. In answer to a question as to the factual basis for structural swirls high above and deep below the topographic profile, the professor tolerantly remarks that in dealing with some sections in the Alps it is necessary to distinguish between their author's facts and his fancies, and he draws a hearty laugh by pointing to a recumbent loop several thousand feet above the highest peaks and saying that he would like to put one question to the author: "Vas you dere, Charlie?" This is the climax of the lecture; the students file out, well satisfied that they are being trained by a scientist with both feet solidly on the ground.

2. One of the professor's young men, having completed his first job of mapping, prepares to walk over the area with an inspector. Forewarned that the inspector is a harsh critic, he plans a "Soviet" tour that threads its way along a route where he is confident of the geologic relations and gives a wide berth to four spots where stratigraphy and structure refuse to make sense and where he knows that he cannot defend his inferred contacts and faults. But, according to the young man's account of the affair, the inspector, on his arrival, spread the colored map on a table, twisted it about into odd positions as he scrutinized it from various angles, glanced briefly at several Soviet-type sections, asked a few searching questions, and finally put his finger neatly, in turn, on each of the four sore spots and said he would like to see each of them. The young man's interpretations in these spots prove to be wholly incorrect, and he later agrees with other young men who have had similar experiences with the same inspector that, in evaluating a geologic map and seeking out critical evidence in the field, the inspector either has X-ray eyes or is in league with the devil.

3. Another young geologist is sketching on a plane table after a round of shots. Working from the near side of the board for convenience, he transfers drainage, topography, outcrops, contacts of several types, and a minor cross fault from his notebook sketch to the plane-table sheet. Then he moves around the table to study the map from a different direction and vertical angle, is evi-

[1] Manuscript received September 26, 1949.

dently troubled by what he sees, trots back over part of his traverse to re-examine some of the features, and returns to erase the fault, modify an inferred contact, and change the shape of several outcrops. The revised map differs from that first drawn not only in pattern but also in geologic meaning—the first version was wrong and the second right.

These anecdotes relate to a method of geologic map interpretation that is a simple and effective aid in the understanding of maps made by others and—what is perhaps more important—in the drawing of geologic lines in the field. The writer was introduced to the method by E. B. Bailey in 1936, when he was privileged to watch Bailey apply it in grasping, literally at a glance, the structural significance of a swirling outcrop pattern in the Pennsylvania Piedmont that had been missed by two generations of competent geologists by whom the area had been mapped. Subsequent reading shows that the method has been in use in Europe for more than half a century, and there is no doubt that it is well known to many field geologists in this country. But it is rarely treated explicitly in geologic reports, probably (1) because the geologist is not inclined to turn aside from discussion of his area to explain a general method as such and (2) because no one area will provide the variety of examples needed for an exposition of the method. It came to the writer, then a graduate student, by word of mouth from Bailey to replace a clutter of rules-of-thumb, painted models, and block diagrams that had made up his formal education in the relationship between map pattern and structure. The method is outlined here in the hope that it will do the same for others. A secondary purpose is to clarify several cases (Bailey and Mackin, 1936; Mackin, 1944, pp. 16–17; 1947, pp. 13–14) in which structural interpretations were arrived at via the down-structure method, without an adequate explanation of the reasoning involved.

Both the form and the substance of the text have benefited from constructive criticisms by H. L. James and A. E. Granger (U.S. Geological Survey), C. F. Park, Jr. (Stanford), and J. D. Barksdale and Peter Misch (University of Washington).

EXPLANATION OF THE METHOD

Nearly all geologic maps are framed by meridians and parallels, with printing and symbols so arranged that "north is up." This convention has many advantages for the cartographer; its great advantage to the user is that the fixed habit of viewing all maps "from the south" permits him to see the features of any individual geologic sheet in proper orientation with respect to a familiar regional geologic background. The geologic map of Colorado, viewed with "north up," reveals a striking assemblage of typical Rocky Mountain structural patterns; but the same map, hung upside down or with "east up," is a jumble of colors with as little meaning as a quotation out of context.

But most lines on geologic maps are surface traces of inclined planes, the orientation of which is wholly unrelated to the geographic framework of meridians and parallels; if the map is viewed down the slope of these geologic planes, the map patterns are seen as structures. Thus, if figure 1 is so oriented that the observer views it in the direction of dip or plunge[1] (i.e., from the east) and at an angle equal to the angle of dip or plunge,

[1] "Plunge" is used here for the angle measured in the vertical plane, in accordance with a recent report of a Map Symbol Committee of the U.S. Geological Survey (Goddard *et al.*).

the line of section *S–S′* becomes a horizontal surface, the portion of the map toward the observer is the structure below the surface along the line of section, and the portion of the map beyond the line is the structure removed by erosion above the surface. In practice the line *S–S′* may be a straightedge or slip of paper that can be shifted at will, so long as it is kept normal to the direction of dip or plunge of those structures on which attention is focused. Or one can, of course, dispense with the straightedge and see the structure in its entirety without reference to any particular plane of section. Figure 1 illustrates four simple applications of the method, each coupled with a more or less self-evident caution or qualification (discussed below) that must be kept in mind in its use.

A. The folds in the southern part of the map have been drawn with vertical axial planes, so that the surface traces of the axial planes correspond with the surface projections of the fold axes; complications that arise when axial planes of plunging folds are inclined will be treated later. It will be noted that, in the down-plunge view, anticlines and synclines are simply *seen* as such; there is no need for recourse to the rules (oldest rock in center; or pattern convex in direction of plunge, etc., equals anticline) to distinguish between them. The map pattern indicates that the folding is disharmonic, and it follows that the down-plunge view of the map provides a closer approximation of subsurface structure than does any section based on downward extension of bedding attitudes measured along the line of section. Along line *S–S′*, for example, attitudes of bed *2* (solid black) in the limbs of synclines *A* and *C* are identical, but the trough form of bed *2* in syncline *A* is quite different from the trough form in syncline *C*. Minor plications in bed *3* in syncline *C*, observed at the surface near the line *S–S′*, do not occur in stratigraphic units beneath the

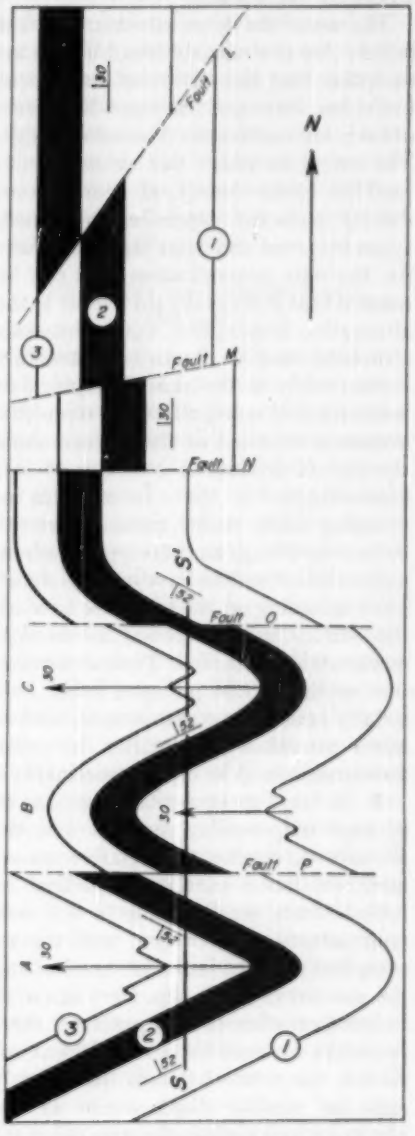

FIG. 1.—Diagrammatic map to illustrate several simple applications of the down-structure method.

surface, whereas observations along the line *S–S'* in anticline *B* fail to suggest the plications that do actually occur in bed *1* beneath the surface.

The use of the down-structure method in this case is obviously based on the assumption that the structural features in individual beds and corresponding parts of folds are continuous down the plunge. The extent to which this assumption is justified varies widely, of course, from district to district, depending on the rock types involved and local structural habits; the only generalization that can be made is that it is usually preferable to the alternative assumption that subsurface structures can be drawn in a structure section solely on the basis of graphical or mathematical manipulation of dip measurements recorded at the surface along the line of section. A corollary to this generalization is that, in an area of plunging folds, *strikes* measured at the surface up-plunge and down-plunge from a given line of section have quite as significant a bearing on the structure beneath the surface in the section as do *dips* measured along the line. To draw a structure section across plunging folds, it is usually necessary to map a zone, with as much attention to precision in strike measurements as in dip measurements.

B. A familiar elementary exercise in geologic map-reading requires that the student determine the relative movement on faults cutting homoclinal or folded strata on the basis of the outcrop pattern after erosion, with the assumption that the faults are vertical and the movement is dip-slip. Here again, as in interpretation of fold patterns, there is usually no need for a roundabout approach via rules-of-thumb; one simply *sees* the relative displacement of the blocks by looking into the map down the bedding planes (fig. 1).

Even if nothing is known or assumed as to the direction or amount of movement on the faults, the down-structure view provides at a glance a correct picture of the stratigraphic throw of any horizon within the moved blocks; on fault *N*, for example, the stratigraphic throw equals the thickness of bed *2*.

In the down-structure view, faults *M* and *L* may at first "look like" high- and low-angle thrusts, respectively. Both faults are actually vertical; they have been included in the diagram to emphasize this important point: that it is possible to look into a map along any sets of planes, but along only one set at one time. Attention is here focused on the bedding planes within the blocks, not on the fault planes between them; and it will be noted that the stratigraphic throw (on *L*, equal to the thickness of bed *2*; and on *M*, one-half the thickness of bed *2*) is readily seen, regardless of the relationship between the strike of the fault and the strike of the beds. Similarly, if one wishes to see the stratigraphic throw on faults *O* and *P*, one has only to twist the map so that the line of sight is down the dip of the bedding cut by these faults; the stratigraphic throw on *O* is one-half, and on *P* one and one-half, times the thickness of bed *2*.

C. The down-structure view of the map pattern of a plunging fold reveals, not the conventional vertical section, but a section that is normal to the inclined axis of the fold. The axis is, of course, by all odds the best line of reference as far as structural relations are concerned, and the "normal section" is unique in being the only type of section that shows the true form of the fold and the actual thickness of all stratigraphic units involved. Bed *2* in figure 1 is, for example, everywhere the same thickness; but this will be evident only if the pattern is

viewed down the plunge of the fold (or, in the northern part of the map, down the dip). The point made here is simply that the down-structure view of a map pattern provides an undistorted normal section that differs from, and must not be confused with, the conventional vertical section, which is always distorted. Other differences between normal and vertical sections are treated later.

D. A third type of structure section is the horizontal section. The down-structure method of map interpretation is based on (1) the fact that each of these three types of sections (normal, vertical, and horizontal) can be derived from either of the other two if the angle of plunge is known and (2) the fact that a geologic map is a horizontal section except that the patterns are usually influenced in greater or less degree by topography. Figure 1, intended as a diagrammatic illustration of the method, is a horizontal section; it is, of course, necessary to take the influence of topography into account in applying the method to actual geologic maps.

The effect of topography on geologic map patterns is adequately treated in standard texts and needs no discussion here. For present purposes the best approach is via the fact that, on a relief model of a rugged area (or the area itself, seen from a plane), the outcrop pattern of a dipping bed is complex from every other point of view, but simple when the model is viewed down the dip. The eye quickly learns to accommodate the influence of topography on map patterns in the same way, namely, by seeing the contoured surface as a relief model. If a map does not carry contours, the down-structure method cannot be applied in matters of detail; the same limitation holds for all other methods of geologic map interpretation.

The examples that follow are intended to emphasize the critical difference between map-pattern trends and true structural trends in areas of plunging folds with inclined axial planes and to illustrate the wide range of use of the down-structure method by applying it in interpretation of map patterns of (1) a simple plunging monocline and (2) a recumbent fold. The first example is a special case, differing from the map-pattern–structure types of problem to which the method is usually applied.

USE OF THE GEOLOGIC MAP AS A RESTORED SECTION

Figure 2, *A*, is part of a large-scale outcrop map sketched from the "near side" of his plane table by the young geologist of anecdote 3 (actually, one of my associates on a U.S. Geological Survey war-minerals project). The dash symbol indicates a lithologic unit consisting chiefly of dark-gray shale and siltstone, well dated by fossils (hereafter called "gray shale"). The stipple is a fine-grained sandstone-siltstone, dominantly reddish, and not fossiliferous (hereafter called "red sandstone"). The conglomerate beds make good ledge outcrops; the gray shale and red sandstone are generally poorly exposed but can be distinguished on the basis of float where the dash and stipple symbols are shown. Blank areas are covered by a creep-wash mantle. All the beds dip steeply to the west on a surface that slopes gently westward; contours are not needed because topography does not significantly affect the map pattern.

On the map (and even more convincingly on the ground) the offset terminations of conglomerate outcrops *A* and *B*, both of which are underlain by gray shale and overlain locally by red sandstone, suggest faulting (fig. 2, *A*). Ce-

mented breccia consisting of gray shale, observed in the float in the area between the terminations, tends to confirm the fault. An abnormal strike attitude in the same vicinity is readily taken to be a drag effect. Human nature being what it is, the south end of conglomerate *D* is regarded as another manifestation of the fault. On the basis of these several lines of evidence, the fault is sketched in with some confidence.

It so happens that the conglomerates contain pebbles of a distinctive felsite porphyry that occurs in place elsewhere in the district; the date of extrusion of the porphyry flows is a problem of considerable importance. The fact that conglomerate *A* appears to be underlain and overlain by fossiliferous gray shale is therefore especially significant; it indicates that the porphyry was available to streams during the time range of the gray-shale fossils. Tonguing of the gray shale into the conglomeratic red sandstone indicates, in addition, that there was no appreciable time interval between the deposition of these unlike, but intergrading, lithologic units; the fossils in the shale therefore serve to date the sandstone.

If the plane-table sketch in figure 2 were colored in as part of the final map on the basis of these interpretations, it would conflict with relationships observed in other parts of the district and would be a "sore spot" of the type noticed by the inspector in anecdote 2.

In the down-structure view of the sketch, from the east side of the plane table, outcrops *A* and *B* are seen not as offset segments of a conglomerate layer dipping about 40° westward on a map but as *flat* sheets of channel gravel at different levels in a section. The difference in level can, of course, be due to faulting of a once continuous bed, but it can also be (1) that the northern termination of the lower gravel sheet simply marks the northward limit of river-swinging at that level against a meander scarp cut in gray shale; (2) that the "gray shale" over this gravel sheet is fan wash shed from the cut bank and adjacent uplands after withdrawal of the river from the base of the meander scarp; (3) that these fan deposits, of local side-stream derivation, intertongue with, and are overlapped by, reddish sands and silts that are overbank deposits representing the suspended load of the through-flowing main stream that carried the gravel as a bed load; and (4) that the channel gravel sheet of outcrop *B* marks merely another position of the channel of the slowly aggrading main stream when, at a somewhat higher level, it planed away the upper part of a fan consisting of gray-shale debris and the higher relief features cut in (solid) gray shale from which the fan had been shed (fig. 2, *B*).

A second look at the field relations with these ideas in mind—and with a little digging where necessary—proves (1) that the critical "gray shale" above conglomerate *A* actually consists of lithic fragments of gray shale; (2) that the covered area over conglomerate *B* is red sandstone, not gray shale, as would be expected if there had been faulting; (3) that the supposed fault breccia rests on conglomerate *A* and is undoubtedly a talus breccia, etc. Revision of the sketch in accordance with these observations eliminates the fault and the associated unwarranted implication as to the date when the felsite porphyry became available for erosion, and it changes the supposed interlensing facies relationship between the gray and red sediments to an unconformity of unknown time value. The gray shale was lithified and dissected before the beginning of red siltstone sedimentation.

It may be noticed, incidentally, that

the revised map shows no local thickening of conglomerate *D*. This overturned esker (?) troubled the young geologist when he saw it in section, and, on more critical examination, it turned out to be a more or less continuous blanket of large conglomerate blocks creeping down the present westward-sloping surface over red sandstone. The change in shape of the conglomerate outcrop is inconsequential in so far as the geologic significance of the map is concerned. But if one subscribes to the philosophy of mapping that makes harmony of contact lines an end in itself (as set forth with contagious enthusiasm by Greenly and Williams [1930] in a chapter that ought to be required reading in every field methods course), then the revision of conglomerate *D* is perhaps no less "important" than the other changes.

The advantage of this special application of the down-structure method is that, by rotating the beds back to flatness, it helps to bring the geologic lines on the map to life as erosional or depositional surfaces, such as might be seen in a restored section or, more directly, in the walls of the Grand Canyon. The method thus tends to enable the student to carry over to his work on maps his "sense of rightness of things" as viewed in section; the case of the overturned esker is a very simple example. The use of the map as a section stimulates thinking as to the meaning of the lines as they are laid down in the field; a glimpse of an unconformity in section, for instance, will bring to mind a flood of possible analogies between that ancient landscape and landscapes now being modeled in similar rocks and structure by a variety of types of erosional processes under a variety of conditions of climate and relief, and these

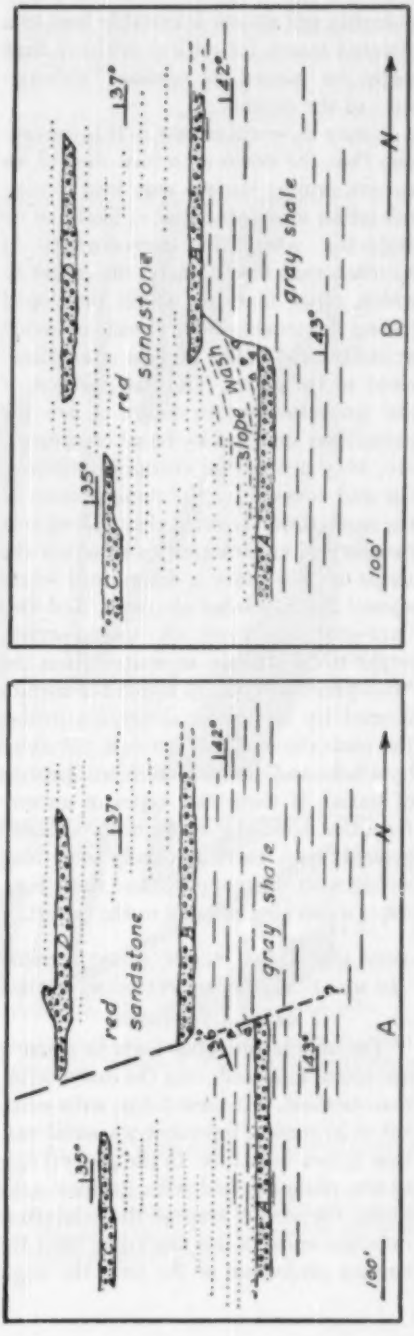

FIG. 2.—Plane-table sketch maps: *A*, as first drawn; *B*, as revised after a directed search for diagnostic evidence.

thoughts will almost invariably lead to a directed search for critical evidence that might be missed in routine "walking-out" of the contact.

It may be worth noting in this connection that the down-structure view of an ancient erosion surface may lead to consideration of a point that is likely to be neglected when the unconformity is merely a map line, namely, the extent to which relief features which developed during the erosion interval were modified or obliterated in the process of emplacement of the cover. The flat portions of the unconformity in figure 2 are *not* peneplanes mantled by basal conglomerate; they are lateral corrasion surfaces, cut and covered by the same process at the same time. As such, they belong in a category of unconformities in which the shape of the surface is determined *by the agency that deposited the cover*, and this "one-process" type of unconformity ought to be sharply separated from the "two-process" type, in which the surface formed by an erosional process during the hiatus is modified little or not at all by a later and distinctly different process of burial. If these two types of unconformities look the same on a detailed geologic map, there is usually something wrong with the mapping, and there is always something missing in the report.

AXIS AND AXIAL PLANE RELATIONSHIPS IN MAP PATTERNS OF PLUNGING FOLDS

GENERAL STATEMENT

The simple plunging folds in figure 1 are useful in introducing the down-structure method, but these folds, with vertical axial planes, represent a special case that is rare in nature. In the general case of the plunging fold with inclined axial plane, the surface trace of the axial plane diverges more or less markedly from the surface projection of the axis, the angle of divergence depending on the plunge of the axis and the dip of the axial plane. The distinction between these two structural elements, stressed by Billings (1942) and others, needs special emphasis in this discussion of map patterns. The surface trace of the axial plane dominates pattern relationships of limbs and noses in plunging folds so completely that the eye tends to be deceived into regarding it as indicating the trend or "strike" of the fold. The "strike" of the fold axis, which is the true "strike" of the fold and by all odds its most significant directional element, may not appear at all in the map pattern. Figure 3 is intended to illustrate this relationship and to demonstrate that the down-structure view of the map pattern will provide a correct picture of the shape of a plunging fold *only if the line of sight parallels the axis.*[1]

The critical difference between the trends of (1) structures and (2) the map patterns produced by them under the influence of plunge has implications that extend far beyond the scope of this discussion of a method of map-reading. Two of the more important of the implications are outlined briefly here because the tendency of the down-structure method to lead the map-reader (or maker) to think along these lines is perhaps its chief long-term advantage.

STRUCTURAL TRENDS VERSUS PATTERN TRENDS

While the direction of the fold in figure 3, as a structure, is due north, essen-

[1] A map and vertical section used in another connection by Billings (1942, fig. 50, p. 63) is an excellent example of the same relationship. The map pattern suggests that the fold trends about N. 45° E.; the influence of the pattern on the eye is so strong that it is necessary to pencil in the surface projection of the axis (about N. 36° E., normal to line of section *M–N*) before the down-structure view of the map will match the section.

tially all inclined planar elements in it strike east of north. This rather anomalous situation results from the fact that the strike is (for practical purpose of measurement with spirit level and compass) necessarily referred to a horizontal plane and is therefore in some respects badly suited for discussion of structures of the type shown in figure 3, in which the strike of every inclined planar element is influenced by plunge. In dealing with structures of this type, horizontal

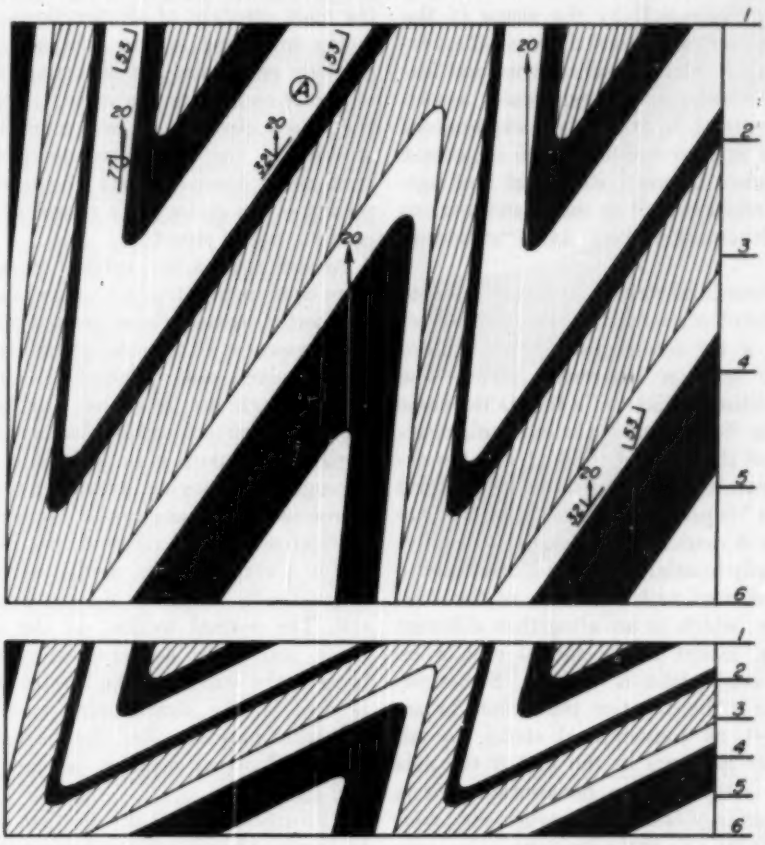

FIG. 3.—Diagrammatic map and section, showing plunging folds with inclined axial planes. North is up. The structural strike is north-south; the plunge is 20° due north. The line symbol used for two of the rock units parallels the strike of the axial planes of the folds.

The section is a normal section, not a vertical section. Angles that appear in the section are structural dip angles, not apparent dips derived from the "true" (conventional) dips shown by figures on the map. The levels *1–6*, from top to bottom in the right-hand margin of the section, correspond with east-west horizontal lines, *1–6*, from north to south in the margin of the map.

If one looks down the structure in the direction of the surface trace of the axial planes (N. 15° E.), the folds will appear to be upright, with notable thinning of all rock units on the steep eastern limbs of the anticlines. The folds are, in fact, overturned, and there is no thinning on the limbs. The structure will be seen correctly only if the map patterns are viewed down the plunge of the fold axes.

and vertical planes are, like the meridians and parallels on a map, simply a convenient reference framework for descriptive purposes. Any genetic treatment must, on the other hand, be based on a framework referred to the axis of the structure, because the whole dynamic history that is expressed by the shape of the fold, as well as all local differential movements recorded by minor structural features within it, are genetically associated with the axis. Two self-explanatory terms help to emphasize the important difference between structural and pattern relationships on maps and sections —"structural strike" and "structural dip."

"Structural strike" obviously refers to the trend of a structure, not to the direction of the intersection of an inclined plane with a horizontal plane. The "structural strike" of a fold is the same as the "direction of the surface projection of the axis" of the fold, but the expression is less cumbersome. "Structural strike" is preferable to "axial strike" because it carries no connotation of applying only to axial areas and is less likely to be confused with the strike of the axial plane, which is an altogether different thing, except in the special case when the axial plane is vertical. Structural strike is the direction that would be assumed, as conventional strike, by all planar elements in the fold if the axis were rotated up to horizontality—it is the strike of bedding, cleavage, etc., *relative to the axis of the structure.*

The chief value of the concept of structural strike is that it guarantees that the field geologist will make a sharp distinction between structural directions and map-pattern directions. One might say, with regard to a group of ledges at *A* in figure 3: "North-south lineation defines the structural strike; the plunge is 20° due north. Under the influence of plunge the bedding strikes N. 34° E., and the axial plane cleavage strikes N. 15 E." A notebook record of this type for many ledges in the map area will make it evident why *B*-lineation, which is a manifestation of structural strike, is usually the most constant of all directional elements measured in the field and will properly emphasize the distorting effect of plunge on pattern relations (strikes) of the planar elements. It will remind the student of the fact, often overlooked, that about three-quarters of the complexity of his geology is a complexity of pattern, not of structure.

As indicated earlier, vertical cross sections of plunging structures always show a distorted cross-sectional form, incorrect thicknesses for all the stratigraphic members involved, and apparent dip angles. These defects are, of course, due to the fact that a vertical section (like a map or horizontal section) is an unnatural slice through the plunging structure; the dimensions and dip angles that appear in a vertical section are referred to a plumb line in a vertical plane, neither of which is genetically related to the structure itself. The normal section, on the other hand, shows the actual cross-sectional form of the structure, the correct thickness of all the stratigraphic members, and what may be called the "structural dip" of all planar elements (see figs. 1, 3, and 4).

"Structural dip" is the dip that would be assumed by the planar elements if the axis of the plunging fold were rotated back to horizontality; it is the inclination of the planar elements *relative to the axis of the structure.* Structural dip is thus closely related to structural strike; but, whereas the direction of structural strike can and should be shown on geologic maps (see below), structural dip cannot

be expressed by any simple map symbol because the angle lies in an inclined plane. The direction of structural dip may or not correspond with the direction of *A*-lineation as observed in the field, but the extended discussion needed even to state this interesting problem has no place here.

We are so accustomed to dealing with vertical sections that we are, like the "captives in the cave" in Plato's *Republic*, likely to confuse the distorted shadows of the structure shown on these sections with the structure itself. The difference between vertical sections and normal sections may be negligible if the plunge is low. But if the angle of plunge is high, all the relationships seen in a vertical section are so badly distorted as to have little meaning for purposes of structural analysis. The geologist who wishes to see his steeply plunging structures as they really are will turn to normal sections, by viewing (1) his map patterns or (2) his vertical sections down the plunge.

The emphasis in this paper is on the utility of the down-structure method as a quick visual method of grasping structural relationships. The *drawing* of normal sections on the basis of conventional data involves all the problems involved in drawing vertical sections and additional steps that are more or less self-evident. Structural-dip angles, for example, can be derived from conventional dip angles by any of the standard methods of engineering drawing (see Beckwith's [1947] handling of the analogous problem of preparing fault-plane sections). Already prepared vertical sections can be transformed into normal sections by a variety of methods, one of the easiest of which depends on the fact that, if any vertical dimension in a vertical section is multiplied by the cosine of the angle of plunge, the product is the corresponding dimension in the normal section.

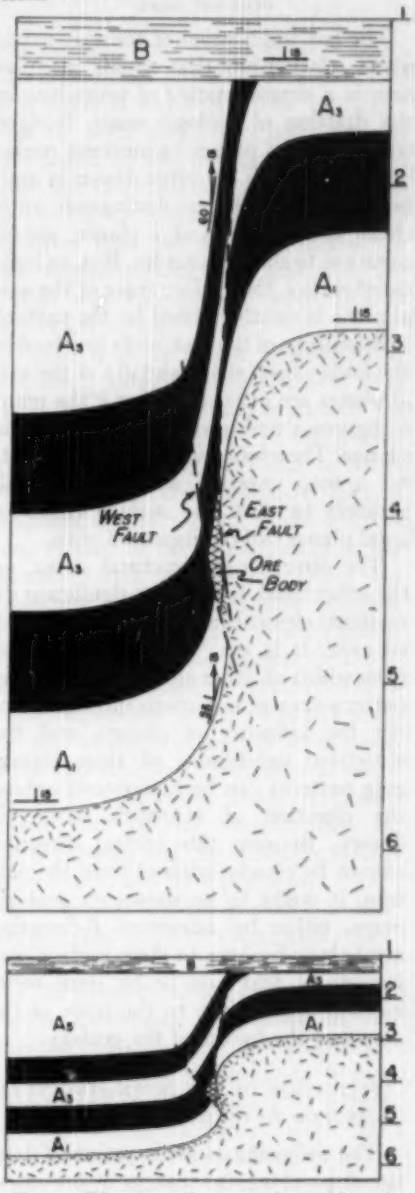

FIG. 4.—Diagrammatic map and normal section of an intrusive monocline

NEED FOR SYMBOLS TO INDICATE DIRECTION OF STRUCTURAL STRIKE ON GEOLOGIC MAPS

The last implication of the axis-axial-plane relationship that merits mention here is a simple matter of procedure in the drafting of geologic maps. Surface traces of axial planes (sometimes mislabeled as "axes") are often drawn in and, because they help to distinguish anticlines and synclines at a glance, are of some use to the map-reader. But, as indicated earlier, the surface trace of the axial plane is clearly defined by the pattern relationships of the rock units involved in the folds—both strike and *dip* of the axial planes are at once evident if the maps in figures 3 and 4 are viewed down the plunge. Therefore, especially if they clutter a map crowded with other detail, symbols to show the surface traces of axial planes can be dispensed with.

The direction of structural strike, on the other hand, is the most significant directional element in the geology of a folded area. It is the "constant" direction from which all other elements of the map pattern diverge in various directions under the influence of plunge, and the structural significance of these zigzagging patterns can be understood only if the direction of structural strike is known. Because this critical direction cannot be closely inferred from the pattern, it ought to be shown on geologic maps, either by numerous *B*-lineation symbols or by lines to show surface projections of fold axes or by some other method appropriate to the scale of the map and the nature of the geology.

APPLICATION OF THE DOWN-STRUCTURE METHOD TO PLUNGING MONOCLINES

The following is a discussion of relationships along the margin of the intrusion in figure 4 as viewed in the usual manner, that is, with the line of sight normal to the page.

> The intrusive border consists of three parts, differing in trend and structure, but grading into each other. In the northeastern and southwestern portions of the area the intrusive contact is concordant at the base of sedimentary sequence A; the sedimentary rocks strike east-west and dip gently northward off the intrusion. In the central portion of the area the same sedimentary rocks dip steeply to the west and are partly concordant and partly in fault contact with the intrusion. South from the faulted segment of the contact the dip of the sedimentary rocks and of the intrusive contact decreases as the strikes swing around to the west. The faults diverge to the north and pass into a monocline that trends slightly east of north. It is noteworthy that the east fault dips into the intrusion and is therefore a thrust at the intrusive contact, but reverses its dip and becomes a normal fault as it grades northward into the monocline.
>
> The faults and the flexure were evidently produced by emplacement of the intrusion. The faults are generally poorly exposed, but drag effects indicate a considerable component of strike-slip movement suggesting that the east (intrusive) side moved northward. Sedimentary sequence B, along the northern margin of the map, rests on an unconformity that bevels the intrusive monocline, and is therefore clearly post-intrusive.
>
> There are replacement ore bodies in limestone unit A 1 in the faulted segment of the contact. Mineralization is evidently limited to this segment and dies out northward into minor alteration effects in the breccia on the faults.

Having drawn this particular map from the section, the writer *knows* what the structure is. The first two paragraphs are not an analysis of structural relations along the intrusive contact (which they purport to be) but a description of outcrop patterns in which each statement emphasizes the incidental at the expense of the essential. Depending on wording, most of the statements range from quarter-truths to three-quarter truths. The interpretation in the third paragraph is entirely incorrect.

The major structure is a faulted intrusive monocline, plunging due north. It is not the intrusive contact but the *surface trace of the contact under the influence of plunge* that diverges from the northerly alignment of the monocline to form the northeastern and southwestern homoclinal segments of the outcrop pattern on the high and low sides of the monoclinal flexure. The structural strike is north-south; it is only the strata of the monoclinal limb that, under the influence of plunge, strike east of north. Decrease in the angle of dip south of the faulted segment is not due to a change in structure from north to south but to the fact that erosion truncates, at progressively lower levels from north to south, a structure that was originally identical in form throughout the map area. The faults do not pass northward into the flexure; they pass *upward* into the flexure, and they are continuous down the plunge beyond the north margin of the map. The change of the east fault from reverse to normal is merely a characteristic of its outcrop; the fault itself is a plane of such curvature that all straight lines within the plane plunge northward. The so-called "drag" that was taken to indicate strike-slip movement is the effect of plunge on the outcrop pattern of beds dragged by dip-slip movement. The faulting was not due to a northward bulging of the eastern part of the intrusion relative to the western part; the faults are breaks in a stretched flexure, along which the roof of the eastern part of the intrusion was raised higher than the roof of the western part. Alteration associated with mineralization does not die out *northward;* it dies out *upward* along the faults. Mineralization is not confined to the place where the faulted part of the contact happens to be exposed at the surface; the same favorable structural relationship continues down the plunge beyond the north margin of the map.

It is often difficult or impossible to determine whether the plunge of a structure is genetically related to the structure or whether it was imposed on the structure by later and independent crustal movement. In this case the fact that the angle and direction of plunge is the same as the dip of sedimentary sequence *B* indicates that the intrusive monocline was originally horizontal and that the plunge was imposed by postintrusion northward tilting.

Figure 4 is, of course, greatly oversimplified. Complicating elements that might be expected in nature include (1) a variety of complexities in the pre-intrusion stratigraphy; (2) one or more generations of deformation structures predating the intrusion; (3) minor structures related to the emplacement of the intrusion, such as bulging along the monocline, cross faulting, and injection of apophyses; and (4) one or more generations of postintrusion structures. It is, in addition, virtually certain that a faulted monocline produced in this manner will actually change in form down the plunge and that its structural strike will be curving rather than rectilinear. Finally, the critical contacts may be poorly exposed and the outcrop patterns may be distorted by topography.

It is in enabling the geologist to look through this maze of extraneous detail, to see the plunging intrusive monocline, that the down-structure method is most helpful. Lineations, joint patterns, and other structural elements in the sedimentary rocks will be understandable only when viewed in their structural setting; they will not fit outcrop patterns influenced by plunge. Contrasted types of primary fracture-and-flow structures in the igneous rock along the east-west and

north-south-trending segments of the intrusive border will fall into place under a roof restored on the basis of the down-structure view of the map pattern. The fracture-and-flow structures in the south-central part of the map area will be different from those anywhere else in the "interior" part of the intrusion and will be in good order or "meaningless," depending on whether the investigator realizes that the intrusive monocline did not terminate where the trace of the contact swings westward but was formerly continuous beyond the south margin of the map. And so forth. In general, without a grasp of the over-all picture, each day's recording of "all of the facts" will only "add to the confusion" and will be a dull business leading to a report of the type that introduced this section. When the picture is understood, the area will offer an exciting opportunity to study a variety of structural relationships in an intrusive monocline exposed from top to base as though seen in a vertical cliff a mile or so in height, except that, instead of being lowered down the cliff on ropes, the investigator merely walks southward to get deeper into the structure. And if the purpose of the study of the district is economic, the grasp of the picture provided by the down-structure view may mean the difference between success and failure of the economic venture.

APPLICATION OF THE METHOD TO COMPLEX STRUCTURES

Bedding attitudes measured at the surface in areas of upright folds and other simple structures can usually be extended downward in a structure section, with reasonable assurance, far enough to provide an adequate picture of subsurface relationships. But it is obvious that this approach will not serve in areas of *décollement* folding or in piled-up recumbent folds and thrust plates or, in general, wherever there are major tectonic discontinuities between structures exposed at the surface and those in depth. It is doubtless for this reason, and because necessity is the mother of invention, that the down-structure method was first developed and has been most used in districts of complex structure. Axial culminations are often said to be key areas in complexly deformed ranges. Perhaps it would be more accurate to say that the culminations are key-*holes;* the key that fits them is the method of looking down into depth along the plunge of structures revealed by map patterns.

Professor X in anecdote 1 missed this point himself and made it impossible for his students to understand the Alpine district under discussion in his class by exhibiting the sections apart from the map on which they were based.

The recumbent fold in the Pennsylvania Piedmont, mentioned earlier, was recognized as such by Bailey on the basis of down-structure study of the geologic map and therefore serves well as an example of the application of the method. The following axioms are much more readily understood against the background of the present paper than they were in the original very brief statement of our case:

1. *If the two boundaries of a formation, under the influence of plunge, follow each other with rough parallelism across the regional strike of fold axes, then the one boundary is* (*structurally*) *at the top, and the other is* (*structurally*) *at the bottom of the formation.*

In the southern part of figure 1 the regional strike of fold axes is east-west, and the stratigraphic units trend generally north-south under the influence of a westerly plunge. The western boundary of each unit is structurally at the top,

and the eastern boundary is structurally at the bottom.

2. *If the two boundaries mentioned in axiom 1 represent the stratigraphic top and the stratigraphic bottom of the formation respectively, then the formation must be involved in a normal sequence of plunging folds.*

This is the case in figure 1, where the structural top and bottom of each unit correspond with its stratigraphic top and bottom.

3. *If the two boundaries mentioned in axiom 1 are stratigraphically equivalent, then the formation must be recumbently folded.*

Thus, in figure 5, the Baltimore gneiss–Setters quartzite contacts (1) near Chatham and (2) at Woodville, both convex to the southwest in pattern under the influence of plunge, are the same contact, and it follows that one of them must be upside-down.

4. *If the observer orients the map so as to look at it in the direction of plunge, he will see the formations disposed on the flat surface of the map in much the same attitude as they would present in a cross section, though, of course, with different proportions.*

In other words, if the observer looks down the plunge, he will see that it is the Woodville contact that is inverted and that the gneiss is the core of a recumbent fold that has its root somewhere off the map beyond *C*, and a down-bent tip at *E*.

A somewhat less mechanical approach to the problem is as follows:

The distinctive map patterns of broad foreland domes and basins, with interformational boundaries obviously influenced by topography, are indicative of low-dipping contacts. When these sprawling patterns (as in fig. 5) are encountered in belts of high-grade dynamic metamorphism, the student will do well to ask himself this simple question: "Do these low dips represent the sum total of the deformation that has occurred in these rocks?" If the ledges reveal intense stretching in small- and large-scale boudinage structures, minor isoclinal folds of types producible only by plastic flowage, or other evidences of great differential movement within and between the lithologic units, the answer to the question is clear. The sum total of deformation certainly must have been very much more than the gentle tilting indicated by the low-angle contacts; the contacts are subhorizontal because deep-seated orogenic flowage on a regional scale has developed folds with subhorizontal axial planes and limbs. Step 1 in this alternative approach is, then, a realization that large-scale inversions are not necessarily restricted to the mountain belts of Eurasia but may be suspected wherever metamorphic rocks show persistent low-angle foliation and contacts, dome-and-basin outcrop patterns superficially resembling those of forelands, or outcrop patterns that swirl across the structural strike.

In such patterns it is possible for the student to draw *one* cross section anywhere, and, if he pays attention only to dips of bedding and foliation and disregards map patterns and plunge, he can draw his one section without showing large-scale inversion, even though half the rocks are upside down. Thus, in figure 5, a section can be drawn along the line *A*–*A'* to show the structure as a simple overturned anticline with a core of Baltimore gneiss; or, a section can be drawn along the line *B*–*B'* showing two anticlines with gneiss cores separated by a syncline with the Wissahickon schist in the center. But *both* these sections cannot be drawn because they fail to comport with each other or with the map pattern and plunge.

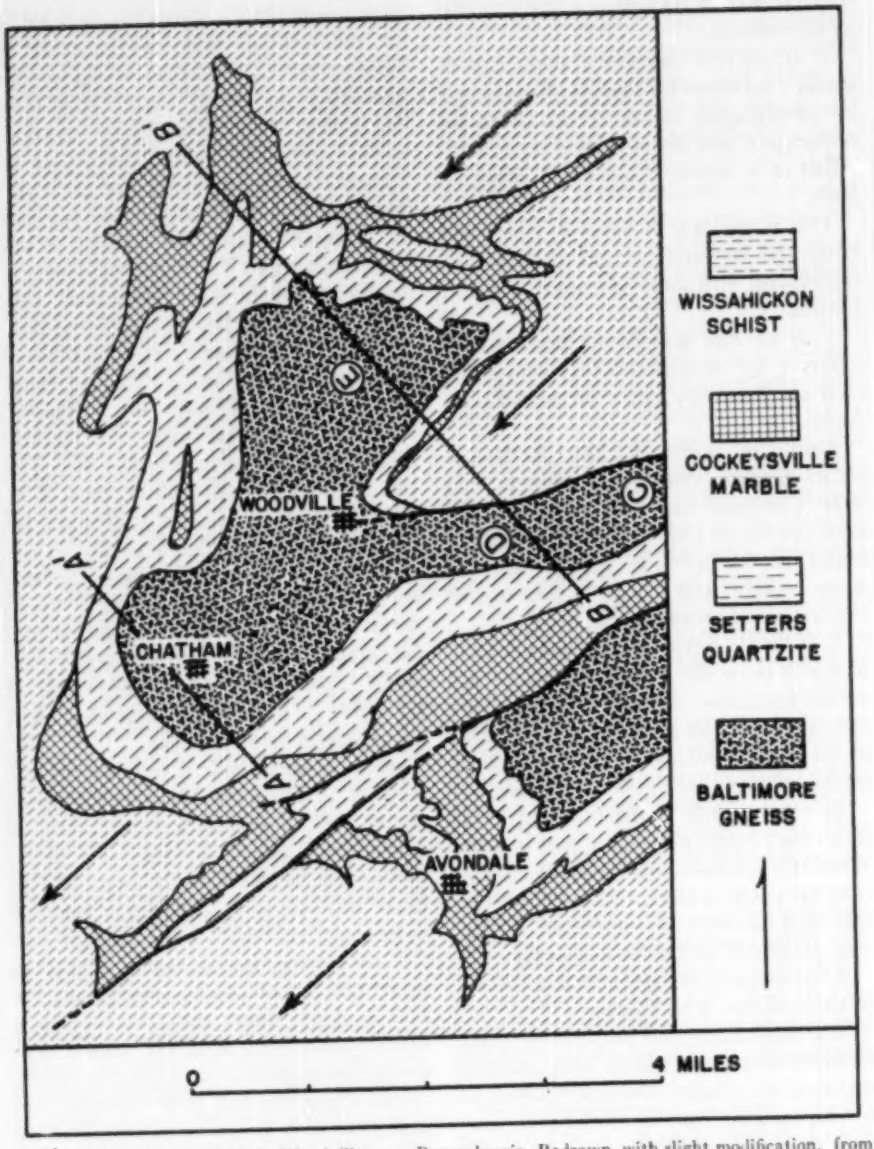

FIG. 5.—Geologic map of the Woodville area, Pennsylvania. Redrawn, with slight modification, from U.S. Geological Survey Folio 223.

The pair of sections do not match each other, because they place a major anticline (in the section along *A*–*A'*) directly on structural strike with a major syncline (in the section along *B*–*B'*). This is impossible because the same belt of Baltimore gneiss is involved in both structures, for this belt cannot be anticlinal on one boundary (the southwest) and synclinal on the other boundary (the northeast). The section along *B*–*B'* would fail to match the pattern due to plunge, because the pattern requires that the supposed Wissahickon syncline northeast of Woodville plunge to the northeast, while all the types of *B*-lineation in this critical area actually plunge to the southwest. The area northeast of Woodville might be said to be "synclinal in stratigraphy" because the youngest rock unit is in the center; but the map pattern and lineation indicate that this area is definitely anticlinal in structure and that the younger Wissahickon is plunging to the southwest under the older gneiss. The Woodville structure must therefore be an arch in the inverted limb of a recumbent fold: the Chatham structure is the same arch in the upper limb.

As far as relationships along the line *B*–*B'* are concerned, the gneiss at *E* might well be the core of an anticline. But when a map shows lineation on the nose plunging under a core that consists of the oldest of the rock units involved in the fold, and when the section shows the structure as a simple anticline, then there must be something wrong with the section or with the mapping. The termination of the gneiss belt at *E* is anticlinal in stratigraphy, but definitely synclinal in structure; it is the diving tip of the recumbent fold.

These conclusions are based on the general principle that, especially in folded metamorphics, linear elements are far more reliable as guides to structure than are planar elements and on the axiom that is the theme of this article, namely, that a section across a plunging structure *must* match the map not only along the line of section but also up- and down-plunge from the line of section.

The down-structure method is helpful in investigation of areas of the type shown in figure 5 because it guarantees that the field worker will grasp the concept of recumbent folding, as a working hypothesis, as soon as his *B*-lineation symbols are sufficiently numerous to guide his eye in viewing his map patterns. If the rocks are, in fact, recumbently folded and if the concept of recumbent folding is not part of the field worker's mental field equipment, then each day's observations will be at variance with what he thinks they should be on the basis of the previous evening's analysis of the mapping to date, and every tentative structure section will conflict with every other tentative section. A little of this type of frustration is perhaps good for the soul; too much of it is likely to drive a doctorate candidate into the life-insurance or brokerage business. The difference between heartbreaking bafflement at every turn and the happier situation in which each ledge fits its mates as snugly as pieces of a jigsaw puzzle may be only a simple twist of the wrist to orient the map so that the patterns are seen as structures. It is, of course, not the down-structure method but the snug fitting of the factual evidence on which the structural interpretations must be based.

Presentation of these interpretations poses a problem that is separate and distinct from the procedures of investigation that led to them. Any section through a complex area of the type in figure 5 must be extended to great depth

if it is to show the inferred structure in its entirety. The use of dotted lines might properly express uncertainties as to details in the deeper parts of the section, but dotted lines are too weak to express the virtual certainty that the section is correct in depth in all essential relationships. It is, in other words, difficult to show in a section, clearly and honestly, all the nice variations between fact and inference, together with the grounds for the inferred parts. There is, moreover, always the danger that the section may be viewed apart from the map on which it is based, in which case it will look fantastic to any geologist accustomed to drawing sections on the basis of dip attitudes alone.

One possible answer to this problem of presentation is to avoid the use of vertical sections, which require long-distance extrapolation from surface observations, and, instead, to transform the map into a horizontal section at any convenient level, as midway between hilltops and valley floors. This involves a minimum of extrapolation and no theory at all. With the topographic distortion of the map patterns eliminated in this manner and with an abundance of symbols showing the direction and plunge of linear elements as well as dip and strike of planar elements, the revised map is, when viewed down the plunge, the most complete and honest manner of illustrating the structure because it is wholly factual. This method requires the co-operation of the reader to the extent of twisting the map, but this is no defect—map-twisting is good exercise for geologists.

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GEOLOGICAL NOTES

PREPARATION OF ORIENTED THIN SECTIONS[1]

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The difficulties encountered in preparing oriented thin sections from rough hand specimens are well known to those who have made such sections. The problem of marking the section and hand specimen so that loss of orientation can be avoided is particularly important to those who have their sections prepared at commercial laboratories. The accompanying figure illustrates a method of marking specimens and chips so that loss of orientation is impossible.

The first step is to fit the slice from which the section is to be made back onto the hand specimen in its original position and mark the surface from which it was cut and both sides of the slice with an orientation arrow, specimen number, and type of section (i.e., *a*, *b*, or *c* section, fig. 1). One side of the slice is then ground to the required smoothness

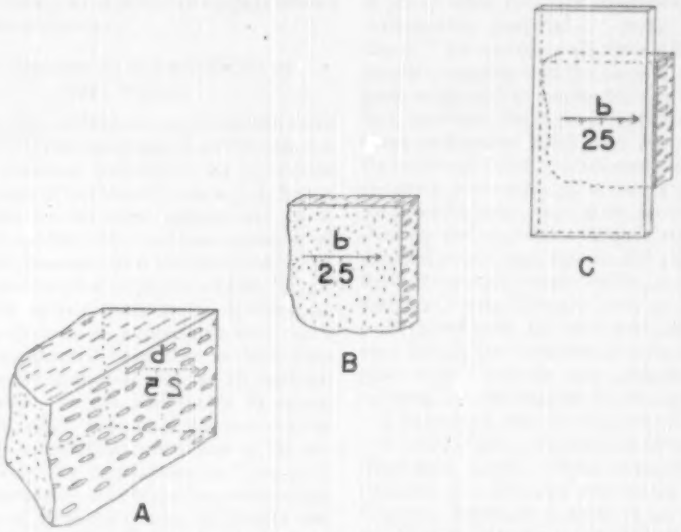

FIG. 1.—Schematic diagram illustrating a method of marking hand specimens and thin sections to prevent loss of orientation during sectioning.

A, Hand specimen showing orientation arrow, number of the specimen and type of section (*b*-section) marked on the surface from which slice has been cut.

B, After cutting, the slice is fitted back to the specimen and marked on both sides as a precautionary measure. One side is then ground to the smoothness required for sectioning and this ground surface is remarked as shown with a fine-pointed, hard pencil.

C, The ground and marked surface is then cemented onto a glass slide for final sectioning.

[1] Manuscript received October 5, 1949.

for sectioning and this surface is then remarked with a fine-pointed, hard pencil. This ground and marked surface is then cemented to a glass slide for final grinding. The somewhat elaborate orientation arrow has been found to be desirable in the event that a portion of the section and arrow is lost during the final grinding. If one end of the arrow and one of the three "dip" marks is intact after grinding, the orientation record is retained. The final thin section is parallel to the marked surface of the hand specimen and has the original penciled orientation data near its center. The identification marks occupy only a small proportion of the area of a slide and do not interfere with optical measurements.

DISCUSSION

CORYCIUM RESUSCITATUM: A DISCUSSION[1]

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Two interesting contributions pertaining to the problem of *Corycium enigmaticum* Sederholm, the oldest known fossil, have been recently published, one of them by a geologist (v. Straaten, 1949) and the other by a biologist (Hutchinson, 1949). It is the purpose of this paper to discuss some of the viewpoints offered by the two scientists.

THE GEOLOGIST ON THE STRUCTURE OF THE *Corycium*

In his paper, v. Straaten (1949) discusses two examples of slump structures from Finland, one of which occurs at Aitolahti in the immediate neighborhood of the locality where J. J. Sederholm found his *Corycium enigmaticum*. In v. Straaten's opinion, the *Corycium* cannot be of fossil origin, inasmuch as it is more or less linked with the occurrence of slump structures. He emphasizes the rarity of fossil remains of true algae without a skeleton of inorganic material, such fossils being generally restricted to derivatives of fine-grained sediments, whereas at Aitolahti the *Corycium* "occurs abundantly in coarse sandy beds, which often show slump structures or indicate considerable turbulence of the depositing water by crosslamination" (1949, p. 16). The carbon content of the *Corycium* is high as compared with the content in freshly embedded algae, and this leads to a very improbable wall-thickness for the original living organism. Moreover, v. Straaten is unable to see how the compaction of the algal walls could have resulted in the formation of coherent sacs, because the carbonization of algae embedded in a sediment could produce only scattered carbonaceous specks; or because the compaction should have caused irregularity in the thickness of the wall if the coherence of the sac had been preserved. The lack of such an irregularity, according to v. Straaten, proves that the material was embedded in the sediment in, or nearly in, its present state of carbonization. Further, v. Straaten finds no reasonable explanation of the "frequently concentric internal structure of the filling mass" of the *Corycium* and thinks it "hard to account for the occurrence in the same beds of many other sack-like structures, partly of carbonaceous material . . . , partly of hornblende." To overcome all these difficulties, v. Straaten suggests that the *Corycia* are of inorganic origin and are slump balls or spiral balls that represent the tops of anticlinal or synclinal protrusions which were separated from the beds and which participated, as independent units, in the subsequent sliding movements. To prove his point, he presents two illustrations showing the occurrence of the *Corycium* in a slumped mass (1949, figs. 10 and 11), in which the folds are still clearly visible, but he admits that many other *Corycia* occur in apparently undisturbed beds. His final conclusion is that, even though the *Corycium* structure is of inorganic origin, it seems very probable that the carbonaceous material itself is of organic origin.

I have dealt with the manner of occurrence and origin of the *Corycium* in a previous paper (Rankama, 1948*a*), which evidently was not available to v. Straaten prior to the writing of his paper. Inasmuch as many of the points discussed by v. Straaten are elucidated in my paper, it is necessary, in this connection, to refer only to his main arguments. First, I must emphasize that the peculiar shapes of the *Corycium* are rather uncommon and occur, in bedrock, only in the northeast part of the phyllite peninsula. They are found in beds showing little or no evidence of disturbance and no evidence of slumping structures. The other carbonaceous inclusions should definitely be considered apart from the true *Corycium*. The inclusions referred to as *Corycium* by v. Straaten (1949, figs. 10 and 11) are weathered carbon-bearing calcareous inclusions (Rankama, 1948*a*, pp. 400–401; pl. 6) that I interpreted as calcareous concretions sim-

[1] Manuscript received August 1, 1949.

[2] On leave from the University of Helsinki.

ilar to those found in Pleistocene varved clays. The difference between the *Corycium* and the other old witnesses of life was discussed in my paper (1948*a*, p. 414), and it was pointed out that the latter are carbonate relics in limestones and cherts, whereas the *Corycium* consists of native carbon. The *Corycium* is rather exceptional in its composition, and this fact certainly accounts for its rarity and that of other comparable formations in ancient rocks as well, but there should be nothing that contradicts the possibility of similar fossils being preserved elsewhere, under favorable conditions. The studies of A. Kryshtofovich on phytoleims referred to in my paper give a very satisfactory account of the manner of formation and preservation of the *Corycium* rings, both open and closed ones. The concentric internal structure of some *Corycia* may be interpreted as being the result of diffusion; of this phenomenon the calcareous concretions, the carbon sacs with carbon-rich remnants, and the disseminated carbon in the mineral grains in the rock within and surrounding the *Corycium* rings afford ample proof. I must conclude that neither v. Straaten's field observations, evidently based on a rather short stay in the locality, nor his interpretation thereof suffice to prove title to his claim that the *Corycium* is of secondary origin. The conclusion of J. J. Sederholm still remains valid, viz., that the original sacs existed—according to my calculation, around 1,400 million years ago—as such in the original sediment. They were carbonized during the decay, under reducing conditions, in the subaquatic sapropelic sediment, and finally, during the consolidation of the sediment and the subsequent metamorphism, they reached their present state of carbonization.

THE BIOLOGIST ON THE FOSSIL NATURE OF THE *Corycium* AND ON THE TERRESTRIAL C^{12}/C^{13} RATIO

There is currently much activity in the study of natural phenomena by means of the isotopes and their abundance ratios, both stable and unstable isotopes being used in such investigations. A particularly fruitful and promising field appears to be the application of this kind of research to the geological sciences, and herewith I propose the name "isotope geology" to cover this field. Current research in isotope geology deals more especially with the stable isotopes of certain light elements, viz., hydrogen, boron, carbon, oxygen, and sulfur (for a recent review see Thode, 1949), and with the long-lived radioactive isotopes of carbon and strontium.

Geologists, physicists, chemists, and biologists alike are interested in isotope geology. The contributions of the geologists, to date, are scarce, the reason being that these scientists are not generally expected to have an intimate knowledge of physics and chemistry and of the laboratory methods concerned. The work of the physicist and of the chemist, on the other hand, is usually handicapped by the fact that he does not pay adequate attention to the established geological truth and to the geological peculiarities of our planet. Therefore, the geologist readily shares the opinion of a distinguished chemist, viz., that "geology frequently suffers from the peculiar nonmathematical character of its logical structure which, to representatives of other sciences, makes its conclusions appear less stringent than they actually are" (Paneth, 1940, p. 14). This reasoning, in particular, applies to the fact that rocks, strictly speaking, cannot be considered completely closed or isolated systems. They are integral parts of the crust of our planet, and consequently they also participate essentially in geological processes taking place therein.

These comments are offered as an introduction to the following discussion of Hutchinson's (1949) paper. He presents the results of a statistical examination on the C^{12}/C^{13} ratios in meteorites and terrestrial material on the basis of the values collected and published (Rankama, 1948*a* and *b*). He finds a highly significant difference in the C^{12}/C^{13} ratio for the following pairs: meteoritic carbon–igneous carbon; igneous carbon–carbon of limestones; igneous carbon–carbon of bituminous sediments. In the pair meteoritic carbon–carbon of bituminous sediments, the difference is only very moderately significant, and none is established between the meteoritic carbon and the *Corycium* carbon. On the other hand, the difference between *Corycium* carbon and igneous carbon is highly significant. Hutchinson concludes that the claim of the fossil nature of the *Corycium*, as based on the isotopic composition of its carbon, is valid only if some difference in isotopic composition between meteoritic carbon and carbon in the uppermost lithosphere is assumed to exist.

There is one aspect in Hutchinson's treatment of the C^{12}/C^{13} ratios that deserves special consideration. If adequate attention is paid to

the existence and effect of geological processes, it at once becomes evident that one cannot deduce any absolutely valid conclusions from the C^{12}/C^{13} averages for the various groups. Inasmuch as geological processes tend to produce changes in the composition of the upper lithosphere, only the ranges of the isotope ratios are significant. I concluded previously (1948*a*, p. 414), on the basis of available data, that in metamorphism and metasomatism (graphitization) there occurs a slight decrease in the C^{12}/C^{13} ratio, pointing toward the concentration of the heavy isotope C^{13}. The variations in the C^{12}/C^{13} ratio of the *Corycium*, even in neighboring specimens collected at the same locality and in the same bed, may be attributed to differences in the degree of metamorphism. Therefore, the highest of these ratios should be the decisive one, provided that the analytical errors for all C^{12}/C^{13} determinations are comparable. If a statistical analysis is made of geological material, it is, in my opinion, highly important to pay adequate attention to the possible effects of the processes by which the material analyzed has been produced. Certainly, statistical examination is a fine tool of research when specimens that have been produced in conditions which may be checked and controlled are compared with one another; but, until there are more data and quantitative data on the extent and intensity of the effect of geological processes on the variation of the abundance of isotopes, it is hardly worth while to speculate with mean isotopic ratios. Instead of a static reasoning, one consequently must apply a dynamic one when dealing with geological material.

It was suggested in my paper (1948*b*, p. 203) that the meteoritic carbon shows the primordial isotopic composition of terrestrial carbon prior to the start of any geological and biological processes in the upper lithosphere and on the earth's surface. The constantly accumulating evidence of the uniformity of the chemical composition of cosmic matter and the recent theories of the common origin of the planets and of the meteorites from a cosmic gas that was chemically similar to the sun and to the majority of the other stars authorize a chemical comparison, both qualitative and quantitative, of the meteorites and the inner geospheres. Many differences in abundance may be explained as being caused by the volatilization of certain elements or of their compounds during the early stages of planet formation. With particular reference to carbon, the original matter might have had a C^{12}/C^{13} ratio of the order of 3, as E. Fermi (see Wilson, 1948, p. 198) has suggested. This value applies to primitive cosmic matter which has not been affected by the cycle of v. Weizsäcker and Bethe. Because interstellar matter presumably is as primitive as can be found, in the sense that probably little of it has ever been incorporated in stars, Wilson (1948) determined the value of the C^{12}/C^{13} ratio in interstellar matter and found, with a fair degree of certainty, as a preliminary lower limit a value of $\geqq 5$ for this ratio. He thinks that the interstellar isotopic ratio for carbon may possibly be as low as McKellar's (1947) value, about 3.4, for nine R-type stars. Bethe's (1939, p. 447) estimate for the C^{12}/C^{13} ratio in the sun is 70, and the primordial ratio in our solar system at a stage when the cooling of the matter excluded further nuclear reactions should be represented by the range in the meteorites, viz., 89.8–92.0. Thereafter, so far as our planet is concerned, the C^{12}/C^{13} ratios found for terrestrial matter display the result of geological and biological fractionating processes.

Hutchinson also discusses the magnitude of the terrestrial C^{12}/C^{13} ratio and considers the possibility that the meteoritic ratio is not inherently likely to be applicable to our planet but presumably is, among other things, a function of the mass of our globe. He concludes that the earth lost more C^{13} than C^{12} during its early cooling. However, Brown's (1949) studies show that the present-day major constituents of the terrestrial atmosphere—water, nitrogen, oxygen, and carbon dioxide—were not retained in any appreciable quantity as gases during the process of the formation of our planet. Brown concludes that these compounds or their constituent elements were retained in chemical combination and only afterward were released into the atmosphere. Consequently, our present atmosphere, as the geochemists have suspected for some time, is almost totally of secondary origin and a result of chemical processes taking place after the solidification of the lithosphere.

The escape of elements from our first gaseous envelope is further elucidated by a recent contribution of Suess (1949). He suggests that the escape of the rare gases after the original condensation of terrestrial matter comprised two phases, the first of which consisted of the escape of the bulk (around 10^7 times as much as the residue) of the still remaining gases from the gravitational field, by convection without any

separation process. The second phase consisted of a preferential escape of the lighter gases from the still remaining negligible residue during a limited interval of time. During the second stage changes in isotopic composition also must have taken place, and therefore it is probable that the abundance of the heavier isotopes of the rare gases in the terrestrial atmosphere is somewhat higher than their cosmic abundance. Finally, Suess points out that the changes in the C^{12}/C^{13} ratio may arise partly from isotopic separation phenomena during the escape of volatile carbon compounds from the gravitational field; but here the isotopic exchange equilibria make the circumstances particularly complicated.

Even this argument, although certainly correct, in my opinion does not invalidate the views on the original isotopic composition of terrestrial carbon presented in my paper (1948*b*). According to Brown and Patterson (1948), until contradictory evidence is presented, the conclusion based on present-day data appears irrefutable: that the meteorites once were integral parts of a planet, similar to our planet in general physicochemical characteristics. This terrestrial planet, just like the earth, has, of course, lost its first gaseous envelope, and therefore the abundance of elements in its fragments is comparable to the abundance in the deeper geochemical spheres of the earth. Carbon, in the form of graphite, is a rather common constituent of the meteorites; and, as far as its abundance goes, the meteorites, on an average, contain a little more carbon than do the igneous rocks: the atomic abundance of C per 100 Si is 0.33 in the meteorites and 0.27 in igneous rocks (Goldschmidt, 1937, p. 99). From analogy with the meteorites there is reason to believe that the abundance of carbon in the deeper parts of our planet is higher than in the igneous rocks of the upper crust.

Hutchinson further deals with Wickman's (1941) and Kamen's (1946) calculations on the amount of oxidized carbon in limestones and of reduced carbon in the biosphere. He finds that they lead to values inconsistent with geochemical evidence if the average C^{12}/C^{13} ratio in meteorites is taken as a standard. He claims that the meteoritic mean cannot apply to the original material of the accessible lithosphere and of the biosphere unless, by a nonbiological process, C^{13} was slightly impoverished in the superficial layers prior to the separations involved in the precipitation of calcium carbonate and in photosynthetic fixation of carbon.

Kamen (1946, p. 129), in his calculation, used the average C^{12}/C^{13} ratio of 89.4 for all igneous carbons analyzed by Nier and Gulbransen (1939). As Wickman (1941, p. 420) has already pointed out, such a procedure is geologically untenable. Wickman himself used the ratio for diamond, corrected to give 89.5, inasmuch as no very strong objections can be raised against the use thereof. Considering that the calculation of the amount of carbonate carbon and reduced carbon should be based on changes in the isotopic ratio during the geological evolution of our globe, there certainly is no fundamental objection to Wickman's calculations. However, one must remember, as Wickman clearly states, that the average ratios which he used for reduced and oxidized carbon are necessarily uncertain, a conclusion which also follows from the principles discussed previously in this paper.

Hutchinson wants the original material, with a probable C^{12}/C^{13} ratio of 89.82–90.66, to produce both carbonate and reduced organic carbon. He does not consider the production of magmatic carbon from the original material, as if no changes were possible in the isotopic ratios in igneous processes. But it is known that inorganic processes tend to concentrate C^{13}, and therefore it is necessary to consider seriously the possibility that the C^{12}/C^{13} ratio of the original material once decreased in magmatic processes and still continues to do so. The formation of limestones and the biological processes are geologically younger than the first plutonic processes that took place in the upper lithosphere. Inasmuch as deep-seated processes in the crust, starting with an early stage of the planetary evolution, may well be considered instrumental in affecting the C^{12}/C^{13} ratio and in modifying the original ratio to approach the range now found in igneous carbon, it is unnecessary to have recourse to a prebiological impoverishment of C^{13} in the superficial layers of the lithosphere. Moreover, as is clearly stated in my paper (1948*b*), I believe that the *original*, or *primordial*, isotopic composition of terrestrial carbon corresponds to the range found in the meteorites, but I do not believe, as Hutchinson (1949, pp. 28, 29) claims, "that the best estimate of the ratio for the earth as a whole is obtained from meteorites" or "that the meteoritic ratio is also the ratio for the earth as a whole." The whole argument given by Hutchinson is based on the misrepresentation of my hypothesis.

The final proof of this hypothesis, of course,

depends on future results of isotope analyses of carbon and its compounds from meteorites, volcanic gases, igneous rocks, and other geological materials. The research now being conducted in Sweden will certainly give much welcome information on the relationships between the carbon isotopes and geological processes. It is hardly too bold to predict that future refinements in mass spectrometric technique will produce valuable results in the field of isotope geology in general.

In conclusion, it is well to remember that geology is wedded to the doctrine of causality (Bowen, 1947, p. 265) and that the laws of statistical probability are not always, off-hand, applicable to geological research material. The geologist of today will find himself steering an uneasy course between Scylla and Charybdis—physics and chemistry—and, unless he is able to fight against those perils with their own weapons, he is a goner, being ultimately confined only to the realm of field geology.

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REVIEWS

Principles of Petroleum Geology. By CECIL G. LALICKER. New York: Appleton-Century-Crofts, Inc., 1949. Pp. 377+xii; figs. 157; pls. 8. $5.00.

This book provides a well-rounded introduction to petroleum geology. An outstanding feature is the chapter on the geographic and stratigraphic occurrence of petroleum, which provides an over-all review of the more important petroliferous areas and the distribution of oil-bearing rocks in the stratigraphic column. This chapter is followed by a brief treatment of the physical and chemical properties of petroleum, designed to acquaint the student with the principal characteristics and properties of oil and gas. The origin, migration, and accumulation of petroleum are covered in forty pages; but, despite the brief treatment, the salient features of alternative theories are presented. The properties of reservoir rocks, the classification of traps, and the origin of structures complete the first section on general principles and basic concepts.

Chapters ix through xiii cover specific types of traps, including anticlines and domes, faults, salt domes, buried hills, and stratigraphic traps. Examples are drawn from many areas, principally in the United States. The treatment covers the location and history, the type of structure, the producing horizons, and production data.

Chapter xiv treats of petroleum discovery methods, considered largely from a historical point of view. The successive sections include surface methods and indications, subsurface methods, geophysical methods, and geochemical methods. The treatment is necessarily brief, but the author attempts to give the essentials of each method of approach. The closing chapters of the book cover geological considerations in petroleum production and the valuation of oil and gas properties.

The text is logical in organization and ambitious in scope. Limitations imposed by semester hours have probably influenced the author in the amount of detail provided on each topic. The style is uniformly good throughout, and the illustrations have been selected to bring out the salient features of the discussion. Within the limitations imposed, the author has included a large amount of information, but certain gaps are noticeable; for example, in the treatment of the origin of structures, no mention is made of the concept of contemporaneous structural growth, nor is McCoy's classic paper on the subject included in the chapter bibliography. No electric logs are included or discussed, despite their almost universal use in subsurface correlation and exploration. Darcy's Law, of fundamental importance in the movement of oil and gas, is stated in terms of an inverted pressure differential, with no treatment of the more general case.

The reviewer is aware that it is much easier to review a book than to write one; and the criticisms expressed are his reactions to the treatment of several topics noted during the reading. Despite these limitations, the book serves the very useful purpose of bringing an important subject into a convenient form, adequately designed to serve as an introduction to the subject. The nongeological reader, interested in the scope of the science, is given an orientation to the field; and the instructor, using the book for class purposes, has an opportunity of expanding such topics as he may wish to emphasize. Professor Lalicker is to be congratulated on compressing a very large subject into a convenient and usable volume.

W. C. KRUMBEIN

Lunar Catastrophic History. By J. E. SPURR. Concord, N.H.: Rumford Press, 1948. Pp. 253; figs. 46; pls. 1.

Lunar Catastrophic History is the third volume of a series entitled "Geology Applied to Selenology," written by J. E. Spurr. The previous volumes are entitled *The Imbrium Plain Region of the Moon* and *The Features of the Moon*. The three books comprise the most extensive and detailed description of lunar features that has ever been published.

In the present volume Spurr continues to develop the thesis that the moon's surface features are the result of internal lunar forces which produced volcanic activity differing from known terrestrial volcanism both in type and in scale.

He conceives the craters of the moon to be enormous gas bubbles which have collapsed.

Lunar Catastrophic History is divided into three parts, namely, "Special Studies in Crater Growth," "The Earlier Proteroselene," and "Problems of Lunar Diastrophism." In the history of lunar events Spurr develops a triple time division, consisting of the Proteroselene, the Mesoselene, and the Teleoselene. In his attempt to classify and systematize lunar features and events, the writer has discovered many significant relationships.

Spurr's treatment of the subject matter is entirely descriptive and qualitative. The extensive detail, the frequent use of a "coined" vocabulary, and the complicated organization make the book difficult to read. Use of tables and graphs to synthesize the subject matter would have improved the book. The figures, all of which are sketches of lunar features, appear to be somewhat subjectively drawn, in that they show detail beyond that which is obviously present on the original Mount Wilson and other photos.

Spurr dismissed the meteoritic-impact theory of the origin of lunar surface features in a few words in the addenda to volumes 1 and 2. However, his explanations for the various types of lunar craters and certain other features are not convincing because he has been compelled to hypothesize a complicated and improbable sequence of events. One might still question his basic assumption that all lunar features are related to internal forces and are not meteoritic.

ROBERT S. DIETZ

The Face of the Moon. By RALPH B. BALDWIN. Chicago: University of Chicago Press, 1949. Pp. 239; pls. 17; figs. 26. $5.00.

The Face of the Moon is a concise and scholarly book with an attractive format, which develops and probably demonstrates the meteorite-impact theory of the origin of lunar surface features. The subject is well organized, readable, and factual, although Baldwin does occasionally invoke the astronomers' prerogative to wax poetic. The organization of a large amount of data into tables and graphs is especially good. This book is clearly the best treatment of this subject that has been published to date.

This book begins with a brief historical summary of the history of selenography. Chapter ii describes the various types of lunar features. The third chapter discusses some of the various hypotheses that have been advanced to explain lunar features and discards as inadequate all theories excepting the meteoritic-impact theory. The next two chapters describe present-day terrestrial meteorite-impact craters on the earth's surface and the so-called "cryptovolcanic structures," which Baldwin suggests are fossil impact structures, following, in this respect, the Boon and Albritton hypothesis. The subsequent three chapters thoroughly analyze many parameters of lunar craters by statistical methods, in an attempt to demonstrate their meteoritic origin. The ninth chapter discusses the problem of the apparent absence of an atmosphere around the moon. The next two chapters are a thought-provoking development of a hypothesis of the history of the moon and of the formation of the maria, which are also considered to be impact features. The writer's chief new contributions to selenography are presented here. The volume closes with a very brief discussion of possible meteorite-impact features on other planets, which adds little to the book and could better have been omitted.

Weaknesses of the book are few. However, many statements on controversial points are so positively made that they are irksome even to one who agrees with Baldwin's general thesis. Probably the chief shortcoming is the lack of documentation, especially in regard to pertinent papers in geological publications. The author appears to have made incomplete search of the literature because he does not even refer to several papers that have stated a thesis similar to his. Also the classical paper by G. K. Gilbert, which first clearly presented the impact hypothesis, is referred to as "information lost or hidden." When discussing geological aspects of the problem, the author appears to be on unstable ground, and he has resorted to extracting items practically verbatim from many sources, often without reference to the original paper.

The book is to be recommended to geologists, who, in general, are so engrossed with the forces acting from the earth's interior that they fail to look up. Even Gilbert, who first formulated a credible theory of the impact origin of lunar features, refused to accept Meteor Crater as a bona fide impact feature and, in fact, because of his pre-eminence, controlled the thought on this subject for many years. The reviewer hopes that this book will arouse the interest of geologists, who have thus far lagged behind the astronomers, although selenography is most closely re-

lated to geomorphology. Also the final solution of many aspects of this problem lies in geological investigations of such features as the so-called "cryptovolcanic structures."

ROBERT S. DIETZ

Elements of Applied Hydrology. By DON JOHNSTONE and W. P. CROSS. New York: Ronald Press Co., 1949. $5.00.

Elements of Applied Hydrology is a textbook for students specializing in hydrology as applied to surface streams. The book assumes some knowledge of hydraulics, such as the Bernoulli theorem, and the concepts of uniform flow in open channels and of critical depth and energy gradient. A working knowledge of elementary calculus and some knowledge of the concept of least-squares adjustments are also assumed.

The authors correctly define hydrology as "earth science dealing with the occurrence and movement of water upon and beneath the land area of the globe." The introductory chapter is a well-written and clear statement of the practical applications of hydrology and a description of the hydrologic cycle. The student of hydrology may be somewhat disappointed to find that, in spite of the title and the excellent introductory chapter, the authors have chosen to restrict the subject matter in the book to three types of problems dealing with surface streams. These three problems are: (1) What is the annual yield? (2) How will a stream behave in time of drought? and (3) How will a stream behave in time of flood?

The discussions of these topics are thorough, and a clear understanding of the behavior of surface streams may be obtained from a study of the materials given. Such subjects as "unit-graph procedures," "flood routing," and the "general hydrologic bookkeeping equation" are ably treated. As pointed out in the text, during dry periods, streams are dependent upon ground-water flow; yet a minimum of space is devoted to a discussion of this subject. Such complex hydrologic subjects as recharge and the storage of water underground are not discussed.

The authors have made a serious and worthwhile effort to bring together much material dealing with the hydrology of surface streams and to establish this material on a quantitative basis. They state—and the reader is impressed by—the fact that wide latitude for judgment in plotting and analyzing available data is unavoidable. On page 237 the statement appears: "The emphasis, as elsewhere in this book, is on ideas rather than on techniques, and the objectives are to encourage the student to pursue the study of statistics further and to stimulate the more experienced to apply statistical methods to hydrologic problems." The statistical treatment itself is a method rather than an idea, and much space throughout the book is devoted to the development of graphs and curves. In the hands of skilled, imaginative people statistical studies may well lead to the development of original ideas; but such things as the descriptions of the small Price current meter and the physical installations of a gauging station seem out of place.

Graphical examples of many data obtained from surface streams are given, but most of the examples are chosen from streams in Ohio, an area with which the authors are probably most familiar. These examples are well chosen, but the usefulness of the book would probably be enhanced by the inclusion of examples from other areas. For example, on page 127 the statement appears that "dry weather periods are usually short, and, for this reason, depletion curves are plotted as a combination of several arcs of the hydrograph. . . ." Dry-weather periods in many of our western states are frequently of several months or more in duration.

The book is carefully written, though the style is somewhat involved and the precise meaning is not always clear. For example, on page 202: "By the use of such a relation curve, a hydrograph of inflow may be computed, reaching zero at the point of inflection and equal to the outflow at the outflow peak, with a total volume equal to the outflow volume and with a peak near the point of inflection on the rising side of the outflow graph."

The book is a worth-while contribution to the study of the behavior of surface streams, but the choice of title unfortunately leads one to expect a much wider treatment of the subject of hydrology than is given.

CHARLES F. PARK, JR.

Sedimentary Rocks. By F. J. PETTIJOHN. A Review and Discussion. New York: Harper & Bros., 1949. Pp. xv+526; figs. 131; pls. 40; tables 139. $7.50.

Sedimentary rocks cover almost three-quarters of the continental surfaces, the balance being made of metamorphosed sediments and possibly of granitized sediments. In a way, sedimentary rocks are the alpha and omega of accessible petrology. Sorby, who invented the

petrographic microscope, did his first work on sediments. Regardless of this, sedimentary rocks have been the "poor relatives" of geology, almost entirely ignored by classical petrographers of the igneous type and suffered for many years by stratigraphers as an annoying but inescapable adjunct to their fossil studies. There is no basic difference, either in degree or in kind, between igneous rocks, metamorphic rocks, and sediments, but this fact certainly does not emerge from a study of the literature on sediments published during the last eighty years. Even the generally used name for the subject, "sedimentation," implies a different and somewhat esoteric context, as contrasted with plain igneous petrology.

It is only fifteen years ago that the petrology of sediments reverted (at least at a few institutions!) to the classical methods of igneous petrology and modern scientific philosophy, namely, a detailed study of the rocks in thin sections, a proper quantitative treatment of all results, and an attempt to tie these basic descriptions with understandable dynamic methods of origin. Pettijohn's textbook on *Sedimentary Rocks* summarizes in an able way the results obtained during these fifteen years.

Since a rock—or, for that matter, any solid—consists of something put together in a certain way, it is necessary before arriving at any broad generalizations to have a firm grasp of composition and texture, particularly composition, because before you put anything together you must first have something to assemble. The study of composition is fundamental. In igneous rocks such studies were well completed by Zirkel in 1885. In sediments these studies are barely beginning. The mineral bulk of the sediments was literally barely glanced over, and all the emphasis was usually put on the accessory heavy minerals or on certain elements of texture or on some far-fetched mass property like permeability. Pettijohn escapes this mistake and devotes his description of mineral composition (chap. 3) almost entirely to the treatment of major mineral constituents (quartz, feldspar, clays, carbonates, etc.). This chapter could easily have been tripled in length, but the amount of published literature on the subject is skimpy indeed, since all first-class petrographic studies of sediments can be counted on the fingers of one hand, one of these being Pettijohn's own monograph on Archean graywackes.

The putting-together of the mineral constituents is exhaustively treated in the chapters on texture and structure; together, they exceed more than one hundred pages, which include a description of the size, shape, and field structures of sediments. Pettijohn covers this field exhaustively and very well. Careful reading of the material, however, shows how contradictory and disorganized the results are in this "area" of sedimentary knowledge. Most of the published work, regardless of its emphasis on numerical presentation (a numerological presentation which frequently masquerades under the name of "quantitative" results), is hardly quantitative at all, since no valid statistical checks of the real significance of the published material has ever been made. By "real significance" is meant an evaluation of the studied properties per se, divorced from the instrumentation. Pettijohn makes the best of a bad bargain and, wading through a fantastic morass of contradictory data, presents all the evidence pro and con for the numerous textural ideas which are flourishing in this field of sedimentology. Possibly a summary and critical analysis of this subject would have helped, but it is somewhat questionable to what extent such critical appraisal is possible at the present time.

It is in the field of classification and summarized presentation of sedimentary rocks that the book is really notable. Beginning with the early 1940's, when the basic concept of the tectonic control of sedimentary processes was introduced by Krynine (1941) and Pettijohn (1943), it became possible (when coupling with this concept a careful and precise study of mineral composition and of typical textural and structural properties!) to divide sedimentary rocks into three basic series (or "clans," as Pettijohn sometimes calls them). These sedimentary series, which are the arkose (quartz and feldspar), graywacke (quartz and micas), and limestone-quartzite series (quartz alone), can be compared to the granite-rhyolite, diorite-andesite, and gabbro-basalt clans of the igneous rocks. Hence these series provide, finally, an objective and reproducible method of sedimentary identification and classification and tie up in a legitimate way with basic sedimentological processes, as finally controlled by large-scale diastrophic movements of the earth's crust. It may be said that, at last, the petrology of sediments has reached the Rosenbusch stage of igneous petrology, that is, the year 1890. This statement probably summarizes the present status of sedimentology better than any other one. Pettijohn's treatise can be called the first published textbook of the sedimentary Rosenbuschian era and, hence, naturally represents a colossal advance over any

treatise that has been published in the field of sedimentation to this date.

In the field of classification Pettijohn reviews the classical system of Grabau (endogenetic versus exogenetic sediments) and the more modern classification of Krynine (arkoses, graywackes, quartzite-limestones). Pettijohn's own system of classification largely follows Krynine's, although there are some minor differences in terminology and Pettijohn has considerably expanded the system to cover practically all types of sediments. In places Pettijohn introduces a somewhat hybrid usage of combining composition and texture (for instance in fig. 66 on p. 227) which to this reviewer does not appear to be particularly felicitous, since pelites—and tillites particularly!—are quite numerous in the arkoses and not only in the graywackes.

The bulk of the book is devoted to a very good description of sedimentary rocks. In the chapters on conglomerates, sandstones, shales, limestones, and other sedimentary rocks which comprise one hundred and eighty pages, a good treatment of the rocks themselves is given, modern throughout, beginning with the mineral composition and ending, in so far as this is possible, with the mass properties.

Numerous tables, both of mineral and of chemical composition, and reviews of typical texture and structure make these chapters highly valuable for study and reference purposes. A minor matter of terminology, namely, the use of the term "graywacke," deserves some discussion. The classical term "graywacke," meaning a gray grit, originated in Germany and was applied to a rock made up of quartz and a large amount of rock fragments consisting of cherts and, particularly, pieces of low-rank metamorphic rocks, such as slates, phyllites, and schists. The amount of feldspar in such a graywacke is of the order of much less than 10 per cent and may be as low as 3 or 4 per cent. Later on, the term "graywacke" was applied (in Great Britain) to rocks of extremely similar appearance but in which the feldspar content was somewhat higher (up to 20 per cent or more), and this feldspar, a plagioclase mostly, was to a large extent derived from volcanic sources. These were the so-called "tuffaceous grits." Pettijohn, in his work on the Canadian Archean, came in contact with these feldspathic graywackes and apparently adopted them as the prototype for the the term. Krynine, on the other hand, in his studies in the Appalachian region, came in contact with the classical or German type of graywacke (nonfeldspathic) and adopted them as his prototype. Basically, the feldspathic graywackes of Pettijohn are high-velocity tectonic sediments formed essentially in eugeosynclines. On the other hand, the nonfeldspathic graywackes (or "subgraywackes" of Pettijohn) are formed under much less intense diastrophic conditions and are basically related to miogeosynclines. Quantitatively, the nonfeldspathic graywackes of the German or classical type (the so-called "subgraywacke" of Pettijohn) are by far the most common in the stratigraphic section and outnumber the feldspathic graywackes several times (possibly 3 to 1), a fact which is somewhat grudgingly recognized by Pettijohn on page 257. It seems, hence, that there is no reason to demote the nonfeldspathic graywacke, which is the original type term coming from Germany and which is also by far the most common kind of graywacke and, furthermore, the most abundant single sedimentary type in existence, and to confuse the issue by inventing the term "subgraywacke." Since the only difference between a feldspathic (relatively rare) and nonfeldspathic (much more common) graywacke is the amount of feldspar in the rock, "common graywacke" "feldspathic graywacke" would be better and more understandable terms.

The last part of the book is devoted to the genesis and origin of sediments (weathering, transportation, lithification, and diagenesis) and adds up to one hundred and thirty-five pages. It is in this part of the book that Pettijohn applies the modern concept of diastrophism and tectonic control to an interpretation of the formation of sediments. The amount of brand-new information, including a very thorough comparative numerical analysis of the lithologic distribution of rock types in various geosynclines, epicontinental regions, and orogenic belts, should be an invaluable eye opener not only to the petrologist but also to the stratigrapher, the regional geologist, and naturally the petroleum geologist.

The chapter on weathering is fairly conventional and a trifle light; the chapter on transport reintroduces the concept of size and shape from the point of view of their possible origin, and again we observe the confusion which exists in the literature on the subject. The chapter on deposition is remarkably good. Pettijohn goes, lock, stock, and barrel, for a complete tectonic control of sedimentation and rejects almost entirely the concept of geographic environmental control so dear to classical sedimentationists.

This controversy (which at the present time is a popular subject) is fundamental, since it covers the relationship between physiographic environments (which can be compared to machine tools in a factory) and diastrophic intensity (which can be compared to the amount of energy being fed into these machine tools). There is, however, a third variable, namely, the type of raw material which is fed into the machine tools and which also depends upon depth of erosion and hence on diastrophism. This third factor, however, is hardly, if at all, discussed by Pettijohn. Fortunately, he considers diastrophic rates in terms both of uplift of the source area and of subsidence of the basin of deposition. Hence his conclusions are on much sounder grounds than are some of the recent publications on sedimentary tectonics, in which only subsidence is considered.

Regions of deposition are divided basically into geosynclinal facies, postorogenic terrestrial facies, foreland facies (epicontinental), and miscellaneous, such as abyssal and mixed sediments. Critically, this means that Pettijohn, to some extent at least, reverts to the geographic environmental concept, this time in terms of tectonic basins. By the way, the same remark can apply even to a greater degree to the recent papers of Krumbein, Sloss, and Dapples. A completely diastrophic approach would consider tectonic regions only as loci of application of pure force, regardless of their physiographic or structural morphology. Perhaps in such an approach lies the final answer to sedimentary genesis. However, this problem is a bit too Einsteinian, at least for the present, and an immediate solution is not in sight.

The chapter closes with a discussion of cycles and rates of sedimentation. The ratios of sandstone, shales, limestones, and conglomerates are shown in diagrams which every geologist would do well to study. Unfortunately, it is in this most valuable chapter that the errors of composition and proofreading reach a maximum. For instance, figure 116 contradicts the text (the text is right). In figure 115, diagrams *C* and *D* are reversed, and, furthermore, each diagram is wrong, since the shale is mislabeled as limestone. This can be corrected by comparing figure 115 with table 131, which gives the same data (correctly this time!) in numerical form. Furthermore, in figure 119, again diagrams *A* and *B* are in reverse, as becomes evident from studying table 133. These irritating errors, however, do not detract from the great worth of the presentation.

In the final chapter on lithification and diagenesis, Pettijohn reviews this thorny field and takes a very definite and positive stand on the allegedly great influence of late intrastratal, epigenetic processes in determining the final complexion of sediments. This reviewer disagrees with two of Pettijohn's concepts, namely, the supposed *late* epigenetic replacement origin of cherts (presumably after deep burial) and the large-scale removal of unstable minerals by decomposition after burial within sediments. Pettijohn believes that heavy unstable minerals get destroyed in sediments with time, a theory which would account for the paucity of unstable accessories in the Paleozoic. However, when it comes to another equally unstable component, this time a major constituent, namely, feldspar, Pettijohn believes that the presence of feldspar is an indicator of tectonism and relief during sedimentation (pp. 440 and 93). Table 25 on page 93 shows the completely *abrupt* break between the feldspar content of Paleozoic sediments (average 3 per cent) and Mesozoic and Tertiary sediments (average 25 per cent). It so happens that exactly the same type of break also takes place in the distribution of unstable heavy minerals, a fact which becomes apparent from a consideration of figure 125. Obviously, it is difficult to claim, and even more difficult to believe, that the presence or absence of major unstable constituents is controlled by tectonism whereas the presence or absence of unstable accessories is controlled by intrastratal solution (which solution, furthermore, is not gradual but appears to have been considerably checked after the Permian!). The reviewer believes that both factors are operative but that primary tectonic control probably accounts for most of the occurrence and distribution of these unstable minerals. The origin of secondary silica and cherts is discussed at considerable length, and siliceous oölites (and oölites in general) seem to be a favorite of Pettijohn. Out of the hundred microphotographs in the book, oölites are represented by not less than twenty, eight of which are siliceous oölites.

As stated before, the appearance of Pettijohn's textbook marks the beginning of a new era in sedimentology. Hence it may not be amiss at this stage to take stock of the development of sedimentology and compare it with that of igneous petrography. The study of igneous rocks got on the right foot from the beginning. Rock-forming minerals were studied first, their textural association immediately after that. This work, carried out with extreme precision and on

a large scale, was completed in twenty years. Only after that did generalizations and interpretations begin to emerge. Furthermore, all this work was done under the tranquil conditions of a strictly academic environment, without industrial pressure of any sort. By 1890 igneous petrography was strongly on its feet, and it is only recently, when it began to go into semicosmogonic fields—fields which require the statistical evaluation of mass properties (beginning with chemical composition and ending with some far-fetched geophysical data)—that igneous petrology has begun to run into difficulties.

In sedimentary petrography the reverse was true. The basic elements of composition were left alone, and the petrography of sediments consisted mostly of beating around the bush and work on the fringes of the subject—heavy minerals, the rounding of sands by rivers, red beds and arid climate, environmental significance of histograms of grain size, and the like. In igneous petrography, beginning with 1875, Ph.D. dissertations, dealing with detailed descriptions of igneous minerals, textures, and entire igneous bodies, were turned out year after year in large numbers and have reached hundreds at the present time. In sedimentology such doctoral dissertations, written in the Zirkelian spirit, probably do not exceed three in number, including one by the reviewer. When it came to generalizations and interpretations, such a lack of fundamental knowledge was not helped by the fact that for the last thirty years sedimentary petrography got indissolubly married, for better or (possibly!) for worse, to the oil industry—a line of human endeavor in which a problem is supposed to be solved within thirty seconds of arising. Now fundamental *basic* research (as contrasted with *applied* research, which can also be fundamental and high grade but is never basic) *cannot* be properly done in a nonacademic high-pressure environment, regardless of what may be said to the contrary. It is fortunate that Pettijohn's work was done, as a whole, against a completely academic background. His book proves it. It is unfortunate that some of the extremely promising fundamental work on the application of statistics to sedimentary petrography and on fundamental concepts of hydraulic behavior of heavy minerals was not continued under similar academic conditions.

Whatever the reason may be, three eras can be distinguished in sedimentology. They can be epitomized by three recent publications. Twenhofel's "Frontiers of Sedimentary Mineralogy and Petrology," published in 1941, can be said to summarize the era of qualitative sedimentation, an era closely related to classical field geology, in which the qualitative methods which proved so fruitful in the reconnaissance, Murchisonian era of stratigraphy were applied to the study of sediments. Obviously, such qualitative methods of attack have limitations. The next era introduced precise measurements, with considerable emphasis on methodology and a statistical treatment of the results. This era, largely pioneered by Krumbein, can be called the "era of quantitative sedimentology." The achievements and problems of this second era have been reviewed by R. Dana Russell in his recent presidential address to the Society of Economic Paleontologists and Mineralogists. (1949). However, this period, mostly concerned with methods and techniques, still left completely untouched the basic problems of makeup and origin of sediments. The third, the petrologic era or the era of petrography pure and simple (but with emphasis on sediments rather than igneous rocks!), has been in the making for a decade or so, but can be said to begin formally with the publication of Pettijohn's textbook. Let us hope that in this era the petrology of sediments will finally come of age.

Recapitulating, *Sedimentary Rocks* comprises 526 pages, 131 line drawings and diagrams, 139 tables, many of them full of original material, and 40 plates of photographs and microphotographs (100). These plates are about the most beautiful illustrations that the reviewer has ever seen. This book is a milestone in the history of sedimentology and deserves to be acquired by any geologist regardless of his field of interest. The reviewer did not have to pay for his copy, but, if he had not received it free, he would have gladly mortgaged his last shirt to acquire one—the book is worth it!

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PAUL D. KRYNINE

Our Plundered Planet. By FAIRFIELD OSBORN. Boston: Little, Brown & Co., 1948. Pp. 217.

Cool skepticism and the long view are hallmarks of the geologist. His science was born of revolt against the idea of a man-centered universe. His services to modern civilization have been indispensable. He is, in a sense, entitled to take a calm view of many issues which have profoundly disturbed his fellow-men. Erosion is an instance exactly in point. Because it is inevitable and has shaped the earth from its beginning, why become excited about it?

It was George P. Marsh who, in 1874, in his book, *The Earth as Modified by Human Action*, first showed that man had become an active geological agent, to his own frequent detriment. Granting, however, that human activities have considerably increased erosion rates (often geometrically), it is not primarily the visible change in morphology which is serious. Rather, it is the interruption of a biological process of which man is a part and which is vital to his survival—the process of soil genesis. Only with masterly skill in land use and management can human beings substitute a new regime which conserves and maintains a high biological potential in the landscape.

It is thus important to the rest of us that geologists read, ponder, criticize, and build upon Fairfield Osborn's *Our Plundered Planet*. The book falls naturally into two parts, first, "The Planet," second, "The Plunderer." The three opening chapters are down the groove for any geologist, since they set the stage in time and evolution. The fourth chapter deals with the interdependence of living things, sketching some of the principles of ecology and showing man's involvement in them. The fifth, entitled the "Flattery of Science," examines the common belief that applied science can, at any crisis, save us from our own folly. Osborn does not believe that we have been granted any peculiar technological dispensation or indulgence, and it should be most profitable to know how geologists feel about this.

It is the second part of the book, however, which geologists must read for the good of us all. Conservation is not a subject but a point of view, and this implies the continuing collaboration of men with the requisite knowledge, skill, and wisdom. In "The Plunderer," Mr. Osborn surveys each continent in terms of man's effect on biological potential and the reciprocal effect upon him. The record is depressing—a monotonous account of environmental depreciation. So far as the reviewer's observations in Canada, the United States, and Mexico are concerned, it is in no respect overdrawn. It is certainly supported by surveys of the Soil Conservation Service in our own country; by the testimony of such observers as Lowdermilk in China, Vogt in Latin America, Shantz in Africa; and by many other sources equally competent.

Perhaps no profession has a better opportunity, in the course of its far-flung activities, to judge whether Mr. Osborn is right in his estimate of the seriousness of the situation. And if my initial surmise is correct—that the geologist is respected for his cool skepticism and his long view—the members of this profession have a unique responsibility to inform and advise the general public on the grave matters with which Mr. Osborn is concerned.

PAUL F. SEARS

The Atmospheres of the Earth and Planets. Edited by GERARD P. KUIPER. Chicago: University of Chicago Press, 1949. Pp. 366; figs. 91; pls. 16. $7.50.

Fourteen monographs on diverse topics are skilfully put together in this book to form an exhaustive and up-to-date study of a subject usually treated by parts rather than as a whole. The reader will be impressed with the wealth of data which can be brought to bear on the study of atmospheres. The resulting knowledge is of importance in theories of the origin of the earth and solar system and has considerable bearing on the question of life on other planets.

The papers were first presented at a special symposium on the occasion of the fiftieth anniversary of the Yerkes Observatory in September, 1947. As a result of that discussion and of further editing during 1948 to bring the contributions into consistency, significant progress was made in integrating all the available data on atmospheres. Professor Kuiper has written an excellent introduction, summarizing the sources of information and the resulting general picture of planetary atmospheres. The order of the following chapters is from near-by phenomena to the more distant—from the circulation of the earth's lower atmosphere, described by C. G. Rossby (University of Chicago), through the high-altitude phenomena of meteors and aurorae, discussed by F. L. Whipple (Harvard) and P. Swings (Liége), respectively, to spectroscopic studies of the atmospheres of other planets, described by T. Dunham (Mount

Wilson Observatory) and G. P. Kuiper (University of Chicago).

A number of remarkable facts and theories emerge; for example, "meandering rivers of air" are flowing eastward around the earth at 10 miles' altitude with speeds as high as 250 miles per hour. Increasing temperatures at altitudes over 100 miles are caused by far ultraviolet light from the sun, which penetrates very little of the earth's atmosphere before it is completely absorbed in ionizing N, O, N_2, and O_2. There is a high-temperature, isothermal, atomic "spray" at the top of the atmosphere, discussed in an interesting chapter by Lyman Spitzer (Princeton), who shows theoretically that atoms describe free elliptical orbits at altitudes above 400 miles.

The history of the earth's atmosphere is treated by the late R. T. Chamberlin and by Harrison Brown (both of the University of Chicago), who introduce and discuss geological and geochemical data. It appears, from the deficiencies of inert gases, as compared with cosmic abundances, that the earth's atmosphere and hydrosphere are of secondary origin. However, because geological evidence points to essentially tant atmospheric conditions since early Archean time, this formation of atmospheric gases and water must have taken place even earlier. One problem which remains is this: During geologic time large quantities of CO_2 and O_2 have been exchanged between the atmosphere and the lithosphere. How has equilibrium been maintained? It is to be hoped that this book will provide the stimulus and the basis for further geological study of the evolution of the atmosphere.

The last third of the book is devoted to spectroscopic data on other planets, from which temperatures and atmospheric constituents are derived. The results seem to be consistent with the recent theories of Whipple, Weizsäcker, and Ter Haar, all of whom ascribe the formation of the planets to accretion of dust particles in a rotating cloud of dust and gas, similar in initia composition to the sun and stars.

Other highlights include an interesting section on high-altitude rocket research by J. L. Greenstein (Yerkes Observatory), H. E. Clearman (Applied Physics Laboratory), and E. Durand (Naval Research Laboratory); excellent photographs of planetary spectra and of the far ultraviolet spectrum of the sun; a number of valuable tables and diagrams (such as the chemical composition of the earth's atmosphere and plots of temperature and pressure to 120 km. altitude); a complete index; and over five hundred references to previous research papers.

The Atmospheres of the Earth and Planets poses numerous problems, which may require years of research. The very formulation of these problems represents a distinct advance and will make the book one of lasting value.

THORNTON PAGE

Radioactive Measurements with Nuclear Emulsions. By HERMAN YAGODA. New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd., 1949. Pp. 356; figs. 75. $5.00.

Doctor Yagoda's book is another token of the present-day interest in the development that takes place in the borde[r] [a]nd fields between the various branches of sci[e]nce. The book is chiefly a laboratory [ ] for the biologist, chemist, metallurgis[t] [ ]alogist, and physicist in the use of photographic emulsions in radioactive measurements; but the theory of radioactivity and of autoradiography is treated sufficiently to guide the scientist not too familiar with these fields toward understanding the principles of the methods.

Mineralogists and petrologists will be particularly interested in chapters vii ("Alpha-Particle Patterns of Uranium and Thorium Minerals") and viii ("Alpha Tracers in Crystallography and Metallurgy"); and those having cyclotrons or atomic piles available should find chapter xi ("Applications of Beta-Ray Patterns") stimulating reading. The following topics are discussed in chapter vii: the uranium and thorium content of minerals; detection of radioactive emanations; emanating power of polished surfaces; the role of radiocolloids in geochemistry; detection of radioactive mineral grains; structure of altered minerals; radioactivity of rocks; and classification of uranium and thorium minerals in polished section. The spatial orientation of ions of radio-elements in synthetic crystals and in minerals and the activity of crystal faces, among other subjects, are discussed in chapter viii.

The book contains a wealth of information, much of which has not been published elsewhere. It is lucidly written and provides valuable reading matter for all those mineralogists and petrologists who are interested in the "exactization" of their science. The illustrations are carefully selected and of a high quality.

Typographical and other errors are kept at a minimum; however, the Swedish *kolm* and *shale* (!) are included among radioactive *minerals; Ghiorso* is spelled *Chiorso* throughout the book; and the author has omitted himself from the author index. The book contains a valuable and up-to-date bibliography of 700 entries; but, according to the nonrecommendable usage common with the physicists and the chemists, the titles of the papers are not given.

The publishers, who like to publish books crossing the various fields of science, have spared no effort to give this book a very attractive appearance.

KALERVO RANKAMA

Principles of Structural Geology. By CHARLES M. NEVIN. 4th ed. New York: John Wiley & Sons, Inc., 1949. Pp. xiii+410; figs. 250; pls. 7 (in pocket). $6.00.

The fourth edition of Nevin's well-known text presents structural geology in the same order of topics as did the third edition (review in *Jour. Geology*, vol. 52, p. 70, 1944). Apart from minor rewording of sentences, addition or omission of some paragraphs, and different sequence in individual subheadings, the author has left the substance of the book essentially as it was. However, the discussion of the physical properties of rocks has been somewhat rearranged. In the chapter on types of stress, new diagrams illustrate the resolution of compressive stresses on planes within the body.

The new edition has 85 new text figures and diagrams. Several outline maps, drawn from the *Tectonic Map of the United States* and other sources, show the geometric patterns of faults in several interesting districts. The reviewer enjoyed the description of four selected areas illustrating the arrangement of joints (p. 155). E. B. Mayo, who contributes the chapter on structures of igneous rocks, as in the third edition, has added several useful new diagrams and has made a few changes in the text. In the chapter on isostasy, the new work by Vening-Meinesz has been included, with an outline map of the negative anomalies in the Dutch East Indies. A five-page discussion of fundamental features of oceans is appended to the chapter on continents and ocean basins. In the chapter on mountain systems two pages on "forces available" have been added.

A welcome addition in this edition is the last chapter (pp. 329–398), with 54 figures, on laboratory exercises. Orthographic and stereographic projection methods are briefly but adequately explained. Numerous fault problems, three-point problems, determination of true and apparent dips, thickness determinations, location of intersection lines of planes, and many others are discussed, and practice problems with solutions are added. Contour projections are not explicitly mentioned, although the construction of contacts of dipping beds implies some familiarity with the principle. Seven plates, in a pocket at the end of the book, are outline maps to be used for students' problem exercises.

The reviewer is dismayed to read, in the Preface to this edition, the following sentence:

> In the past I thought that specific reference to the source material should be made throughout the text; and that by reading the original discussions the student would be tempted to form his own opinions. Unfortunately, it does not work that way. Beginning students in structural geology seldom read references; and if, by chance, a reference is read, the main ideas of the paper are usually not grasped.

If this is correct, something should be done to improve the situation. Granted that the teaching of structural geology in classroom and laboratory, with books, maps, a few experiments, and, where possible, some field trips, is difficult and can never substitute effectively for direct field experience of students; yet the subject should and, in the reviewer's opinion, can be so presented that at least some students feel the urge to read and ponder original source material. Moreover, textbooks are not written for students only. No man can claim to know the entire literature of structural geology so well that he would not profit from direct reference to technical papers that are new or older ones that he may have forgotten. Many new important references are given at the end of chapters for which every reader will be grateful to the author; but some students may not be able to connect statements in the text with the titles of certain references.

In our opinion the reader's interest in the subject matter can be enhanced if captions to all photographs that show interesting structural features give locations as far as they are known, thereby providing a closer bond between the reader, the theory of a subject, and places on the surface of the earth, without which there would be no structural geology. Likewise, it may do no harm, even in a textbook, to mention somewhere the natural difficulties under which many structural data have been obtained and estab-

lished; the bewildering variability of each phenomenon among rock structures; the vexing scarcity of outcrops in most areas; or the common impossibility of deciding which particular mechanical principle or process has been more important than others in producing a given result. This may explain to the uninitiated why geological interpretation of many structural problems must be cautious and differs significantly from the method of procedure employed in many other sciences.

The reviewer regrets that the book says little about the plastic deformation of rocks at relatively deep levels and the specific problems resulting in mapping rocks of this kind and interpreting their deformational history. Because the days are over when basement complexes were labeled "granite" and given a noncommittal dash pattern, information on structural mapping of crystalline rocks should be given more space than before. Though the number of geologists active in this line of work will probably always be small, our knowledge of the cores of mountain ranges and our concepts of the lower portions of the crust depend on progress of work of this kind. Mapping isograds of mineral facies over many hundreds of square miles increases our knowledge of the structure of the earth's crust just as much as does the mapping and plotting of the lineation, fold axes, planes of early or late flow cleavage, or fracture systems. To distinguish zones of precrystalline deformation from others of postcrystalline deformation may be as important as the mapping of the contacts of an intrusive mass or a series of fault zones. Similarly, a geologist has to know how far he can assume constant stratigraphic thicknesses in crystalline formations and what outcrop patterns result from extreme plastic deformation of such rocks. The author commendably refrains from extended discussion of highly speculative hypotheses of deep levels of the earth. Perhaps, however, a concise discussion of the known structures of the deepest exposed levels will stimulate research in those regions where the geologist can supplement his guesses with a large amount of knowledge and direct observation. Perhaps some of these problems could be discussed in forthcoming editions of the book.

The subject of structural geology is immense; and entirely adequate descriptions and discussions of every subject would expand a textbook so much that its cost would be prohibitive. Within the limitations drawn by cost and scope, Nevin's book, we believe, is one of the best.

R. B.

Theoretical Structural Metallurgy. By A. H. COTTRELL. New York: Longmans, Green & Co., Inc., 1948. Pp. viii+256; figs. 96. $5.25.

It has become apparent in recent years that metallurgy and mineralogy have much in common. Most of the subject matter in Cottrell's *Theoretical Structural Metallurgy* could just as well be called "fundamentals of structural mineralogy": simple and illuminating discussions of the structure of the atom, interatomic forces and atomic dissociations, the structure of ideal and imperfect crystals, solid solutions and intermediate phases; equilibrium and the rate of approach to equilibrium, equilibrium diagrams; a good thermodynamic text of the free energy, specific heat, melting, and solution; polymorphic changes and order-disorder transitions are well treated, together with diffusion and the theory of atomic migration in crystals.

Therefore, the modern mineralogist will find much of interest to his science in this handy and concentrated textbook.

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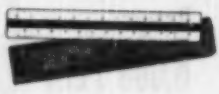

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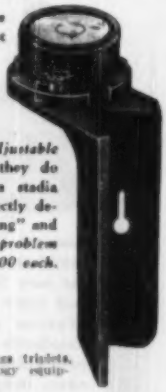

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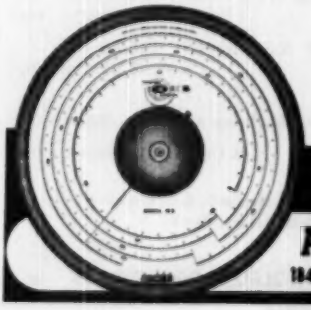

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